Economic and environmental considerations for construction and demolition (C&D) debris management and policy

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ECONOMIC AND ENVIRONMENTAL CONSIDERATIONS FOR CONSTRUCTION AND DEMOLITION (C&D) DEBRIS MANAGEMENT AND POLICY

BY

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B.S. Environmental Management & Policy, University of Maine, 2005

THESIS

Submitted to the University of New Hampshire
in partial fulfillment of
the requirements for the Degree of

Master of Science
in
Resource Economics

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DEDICATION

I dedicate this thesis to Zion and Colin for their support, encouragement, understanding, patience, and love.
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ABSTRACT

ECONOMIC AND ENVIRONMENTAL CONSIDERATIONS FOR CONSTRUCTION AND DEMOLITION (C&D) DEBRIS MANAGEMENT AND POLICY

by

Andria Vachon

University of New Hampshire, September 2008

Construction and demolition (C&D) debris is a significant part of the waste stream in the United States. Recycling is increasingly becoming a more popular method of disposal due to both market and regulatory forces; however, most of the debris is still landfilled. C&D debris facilities handle materials with low value and have few market opportunities. Limited recycling opportunities may be available for hazardous materials. A survey of mixed material C&D recyclers in the United States is analyzed in this paper. Some topics of interest covered in the survey included: end uses and markets for recycled materials; technological processes utilized by facilities; recycling rates of facilities; landfill collaboration; C&D debris fines; tipping fees; materials of concern to facility management. Many facilities do not and are not required to test C&D debris fines prior to beneficial use alternative daily cover (ADC); many respondents have limited market opportunity for demolition drywall, demolition wood, and asphalt shingles. The findings will help stakeholders understand the climate of the industry nation-wide and make informed decisions.
INTRODUCTION

Solid waste management has been a topic of concern for policy in the United States since the early 20th century. Commonly discussed wastes are those considered hazardous due to their dangerous nature and also household waste known as municipal solid waste (MSW) due to the high volume generated annually. However, a waste stream that is more recently becoming a topic of discussion among policy makers and waste disposal managers is construction and demolition (C&D) debris.

C&D debris has historically been bypassed as a critical waste stream to manage due to its generally inert nature and the quantity generated was unknown. Also, this waste stream has been co-disposed with MSW for many decades and landfilled in both C&D debris and MSW landfills. Construction and demolition debris is generated by virtually all sectors of the economy through renovation, demolition and construction processes.

The most recent United States Environmental Protection Agency (US EPA) study estimated that there were 210 million tons of MSW generated in 1996, there are also 136 million tons of building-related C&D debris generated in the US in the same year (US EPA, 1998a, 1998b). This significant volume of C&D debris has prompted federal and state governments examine disposal practices for this waste stream.

It is important for there to be differentiation between C&D debris and MSW both in management practices and regulatory definitions. The materials that comprise C&D debris are physically and chemically different than those materials in the waste
stream and therefore may have different needs and requirements for proper disposal (Clark et al. 2006).

C&D debris is not currently regulated by the federal government, it is regulated at the state level and the degree of regulation and definition of C&D debris varies widely across the nation (US EPA, 1998a; Clark et al. 2006). This causes estimates of the waste stream and its management to be inconsistent in the US. The purpose of this research is to help identify potential solutions to some problems faced by the C&D debris waste stream.

Approximately 40-55 million tons of C&D debris is landfilled annually. This material tends to be bulky and is estimated to take up 25-40% of landfill space (US EPA, 1998a). Land availability for new landfills is scarce in some regions of the United States; for instance, the Northeast is a densely populated region and there is the presence of “not in my backyard” (NIMBY) attitudes causing difficulty in siting new landfills even though space in the existing ones is running out. Landfills are also quite expensive to build and maintain, and often are subsidized by governments (Leigh & Patterson, 2005).

MSW landfills will often accept C&D debris but there are also C&D debris landfills specifically for this waste stream. States generally require MSW landfills to have more stringent leachate and groundwater control technologies than C&D landfills are required to have. Clark et al. (2006) concluded that many states may not be aware of the potential environmental risks that C&D landfill disposal may have without proper liner and groundwater technologies on landfill sites. Some regions with abundant landfill space and low landfill tipping fees may affect the economic viability of recycling facilities.
State Regulation

Typically, state C&D debris waste definitions include waste produced from the construction, renovation, and demolition of buildings, roads and bridges. C&D debris waste materials generally include inert wastes such as wood, concrete, brick, asphalt, metals, gypsum drywall, and roofing. Some states include yard wastes such as stumps, dirt, and rocks in their definitions (US EPA, 1998a). Inert wastes are not readily reactive with other elements or compounds; therefore, C&D debris landfill restrictions tend to be less stringent on groundwater monitoring and liners. In fact, nineteen states do not require any groundwater monitoring or liners in C&D debris landfills (Clark et al. 2006).

However, C&D debris may contain hazardous materials like asbestos, lead-based paint, mercury, cadmium, polychlorinated biphenyls, and chromated copper arsenate (CCA)-treated wood, all of which can cause environmental and human health problems. Hazardous waste is regulated federally either by the Resource Conservation Recovery Act (RCRA). Other regulations governing some of the potentially hazardous materials in C&D debris include the National Standards for Hazardous Air Pollutant (NESHAP) (covers asbestos), the Toxic Substances Control Act (TSCA), (covers PCBs) and the Comprehensive Environmental Response Compensation and Liability Act (CERCLA, more commonly known as Superfund) (Clark et al. 2006). These federal regulations help guide management practices of some wastes that may be contained in C&D debris. Some state C&D definitions specifically preclude these items from the debris, so they should not be mixed together in the first place. It is recommended that hazardous materials be removed from a building prior to demolition; however, often it does not occur (Townsend et al. 2004) which could lead to improper management of hazardous materials. The
presence of hazardous materials in the C&D debris waste stream requires proper management and disposal practices critical to maintaining the health of environments and humans. However, the federal government does not provide guidelines for the management of the general C&D debris waste stream whether it is targeted for landfill disposal or recycling.

Some states are very aggressive and involved in the development of regulations that will be beneficial for the market climate in their respective states. For example, the California Integrated Waste Management Board (CIWMB) has prepared a model C&D debris diversion ordinance for jurisdictions to modify for their own needs, to force diversion of C&D debris to recycling. Then there are states on the other side of the spectrum like Arizona, which has not established rules for C&D debris landfills or recycling (Clark et al. 2006). And then, there are states in the middle, trying to determine what the right regulations are for their respective economies and to maintain environmental and human health. For instance, New Hampshire is currently struggling with making management decisions for C&D debris that can involve tradeoffs between environmental quality and economic wellbeing.

C&D debris disposal regulation varies in degree of stringency across the nation. Perhaps this is due to fragmented and unavailable data of quantities and impacts of this waste stream. Some states have more pressing regulatory concerns that may overshadow the need for C&D debris regulation whether it is for landfill requirements or encouragement of diversion to recycling this waste stream. Proper management is necessary to maintain environmental integrity, human health and to assure "best use" allocation of scarce resources.
Recycling C&D

Diversion of C&D debris from landfills to recycling has many benefits to society, the economy, and the environment. There are many opportunities for economic and community development through recycling of C&D debris, which may currently, in many regions of the US, be treated purely as waste and disposed in landfills. Some economic and environmental benefits that may result from C&D debris recycling include: economic stimulation from jobs created, extended lifespan of landfills, reduced demand for virgin materials, decreased use of toxic chemicals, land conservation, habitat preservation, reduced overall disposal costs, and reduced greenhouse gas emissions (Leigh & Patterson, 2004).

Only about 20-30% or 25-40 million tons of C&D debris are recycled each year (US EPA, 1998a). Barriers exist that prevent increased recycling and recovery of C&D debris: The high initial investment for collecting, sorting and processing the material is often not economically competitive with low landfill tipping fees and recycled content material has a very low value in relation to the cost of virgin based material (US EPA, 1998a; Leigh & Patterson, 2004).

Observation of a building being demolished will leave the observer wondering how the mixed material is going to be sorted and recycled. Mixed debris facilities that process multiple materials that are commingled have highly intensive and technologically advanced processing procedures for sorting debris. These facilities require high capital investments to handle very low valued materials. Often the highly valued metals never reach these facilities, but rather are removed on-site by workers. Mixed C&D debris facilities are particularly vulnerable to market and regulatory changes to disposal and
material requirements. A change in requirements for handling and marketing one material may affect the technical processes and management for other materials due to nature of mixed loads. Therefore, new regulations need to recognize potential trickle down effects that may occur when new regulations are imposed.

Changes in consumer attitudes are helping to shape the direction of C&D debris waste management. The practice of sustainability is becoming increasingly popular in many different sectors of the American economy. Sustainable practices in the building of infrastructure are one such place it may be found, in the form of green building techniques. These techniques include recycling construction and demolition debris from demolition sites and using recycled products in the building processes. The Leadership in Energy and Environmental Design (LEED) Certification for green buildings requires the use of less toxic materials, recycled materials, and recyclable materials, reducing the amount of waste produced, and managing C&D debris generated in a sustainable and environmentally sound manner. LEED certified buildings have had a recent increase in demand therefore there has been a ripple effect in the markets attributed to building and disposal.

However, as with C&D debris landfill regulation variation across states, C&D debris recycling regulations also vary widely. Only 17 states had C&D debris recycling facility requirements in 2006 (Clark et al. 2006). Some states require facilities to have a permit to recycle and sort the material other states do not have these permitting requirements.

Unless there are regulatory incentives recycling facilities cannot successfully compete against landfills with tipping fees lower than the recycling facility’s tipping fees.
Households and construction and demolition companies will choose the lower cost method. A recycling facility has very high initial investment and labor intensive processes for sorting material, therefore there is often a very operationally defined minimum tipping fee; where landfills are often subsidized and sometimes governmentally owned and operated with much less labor and capital investments. A recycler must be able to offer a lower tipping fee than a landfill in a region otherwise there will not be demand for recycling unless there are some incentives for those in need of disposal to choose a higher cost method.

Regulation is used when there is market failure in an attempt to correct it. In the instance of C&D debris management full lifecycle costs are often not accounted for in the decision making process. Lifecycle costs may include the cost of extraction of virgin materials, transportation costs, operating costs, and disposal costs of C&D debris wastes (Leigh & Patterson, 2004). The free market is not currently accounting for these costs, which leads to a need for some regulatory or market changes to include the true costs of disposal.

**C&D Debris Fines**

Recycling of C&D debris is beginning to be pushed by some states and regulators for economic and environmental reasons. Not only do C&D debris facilities have to worry about the more obvious hazardous materials such as asbestos, mercury, and chromated copper arsenate treated wood, but mixed processors also have a byproduct from the sorting process they must manage. This byproduct is commonly known in the industry as C&D debris fines. Truckloads of commingled material are dumped on a tipping floor in a facility and sorted by material type. At the end of the processing line
the final materials are screened (using variable sized screens) resulting in a soil-like material known as C&D debris fines. C&D debris fines generally are composed of small pieces of gypsum drywall, wood, concrete, brick, asphalt, paper, and plastic. The actual composition of the fines is a function of the sorting process utilized by a facility and the materials delivered to the facility (Townsend et al. 2004). C&D debris fines need to be either disposed of or reused; C&D debris fines are twenty percent (by mass) of outgoing material from C&D debris recycling facilities. Without suitable markets and/or safe disposal opportunities for C&D debris fines some recycling facilities may not be able to continue operation.

The composition of C&D debris fines causes difficulty for disposal and reuse. Fines typically have low levels of trace metals that prevent them from being used as clean fill (Townsend et al. 2004). One common use for the C&D debris fines is alternative daily cover (ADC) at operating landfills and for shaping and grading at landfills undergoing closure; however, this use can be problematic due to hydrogen sulfide formation.

C&D debris fines typically have a high proportion of gypsum wallboard which is composed of hydrated calcium sulfate. A landfill is an anaerobic environment in which bacteria will reduce the sulfate and emit hydrogen sulfide (H₂S) and carbon dioxide gases. H₂S emissions are not only a nuisance because of the unpleasant odor but more important can be a health hazard. The odor is detectable at 0.5 ppb, and at concentrations greater than 500 ppb can result in loss of consciousness and death (Flynn, 1998). The rate of H₂S generation depends on the amount of organic matter, concentration of dissolved oxygen in the leaching solution, the temperature, and the pH (Jambeck et al.)
Finding alternative uses and/or finding economically feasible ways to mitigate the H₂S formation is important for human health and the continued operation of mixed C&D debris recycling facilities and is one of the objectives of this research.

**Purpose of the Study**

A greater percentage of the C&D waste stream has an opportunity to be recovered and turned into new material that will benefit our society economically and environmentally. This research is conducted to answer some questions about what existing C&D debris recycling facilities are doing in their processes, with the materials as end uses, and the issues that they face which may be hindering their capability to recycle more material. It is the intent of this research to make recommendations to all stakeholders including policy makers and industry participants which may help capture the lost opportunities of C&D debris that is currently sent to landfills, and divert it to recycling.

C&D debris management has recently become a topic for concern in the regulatory arena. However, policy is best made when there is clear information on the current trends and practices being experienced by an industry. Otherwise, fragmented uninformed decision-making will hinder industry and may cause more harm than the good that was intended. It is the purpose of this research to help create a better understanding to all stakeholders as to the processes and activities that mixed C&D debris recyclers are presently undertaking. There has not been such a study done at the facility level nationwide to illustrate this information.

This research allows regulatory and industry professionals to see into the window of the C&D debris recycling industry. Without consistent or sometimes existent
regulatory requirements for C&D debris recyclers across the US it is impossible to extrapolate what may be going on in one state by what may be happening in another. Therefore this research is necessary for there to be competent and informed decision making at the industry and regulatory level.

**Goals & Objectives**

More information of current national C&D debris recycling practices needs to be made available to policy makers. This will provide a better understanding of the industry. This information will allow decision makers to better determine what incentives and regulations may be needed to increase the percentage of C&D debris recycled and will allow policy makers to see where increased regulation for human and environmental health may be necessary.

C&D debris fines sometimes are a problematic material that needs to be carefully managed but has the opportunity for beneficial use when done properly. A better understanding of the contributing factors and geographic areas that are susceptible to H₂S generation is necessary. The beneficial use of C&D debris fines as ADC in landfills will streamline and minimize unnecessary regulation on facilities that are not at risk for dangerous H₂S generation.

There are also other materials in the C&D debris waste stream including demolition wood, demolition drywall, and asphalt shingles that currently do not have stable recycling markets. The cause of the lack in market opportunities for these materials may be due to environmental and human health concerns, lack of technological research for reuse opportunities or regulation inhibiting recycling.

**Goals**
1. Provide quality information to policy makers about the current C&D recycling industry climate and practices.

2. Provide useful recommendations that will assist policy makers in C&D management requirements which will enable increased C&D recycling.

**Objectives**

1. Analyze C&D debris practices data to enhance stakeholder and policy maker understanding of current practices in the C&D debris recycling industry.

2. Formulate recommendations which will be feasible for C&D debris recyclers to implement to mitigate $\text{H}_2\text{S}$ formation in fines.

3. Formulate recommendations based on the industry climate which will help alleviate market failures in C&D debris management.
CHAPTER 2

METHODS OF DATA COLLECTION AND ANALYSIS

**Hypothesis**

The main goal of this research is to enhance stakeholder and C&D debris waste managers about the current C&D debris recycling industry practices and experiences. The hypothesis however is not currently testable.

\[ H_0: \] Increased understanding and knowledge about the C&D debris recycling industry will allow more effective policy making in the future.

Analysis of the current problems is the second step the US EPA takes when developing policy (US EPA, 2008b). Without understanding the current industry practices and in an arena that is not consistently regulated by the states, it is necessary to actually survey and analyze what C&D debris recyclers are doing. Otherwise there would be information gaps where some states have very little regulation and permitting requirements and C&D debris recyclers are operating.

**Research Design**

The tool thought best to gain further understanding of the C&D debris recycling industry in the US was to send a survey to the C&D debris recycling facilities. We thought that the best way to gain more insight and understanding of the current C&D debris recycling industry was to obtain cross-sectional data from across the US. The survey was conducted during the fall of 2007.
Sample

Facilities that were considered were those that accepted mixed loads of materials, not single stream recyclers. The list of such facilities was compiled from state permitting records, recycling association member listings, internet searches, and regional recycling databases. The EPA estimated approximately 300 such facilities were in operation in 1998 (US EPA, 1998a). There were 422 facilities identified initially. Of these, 275 had complete mailing addresses that were able to be found. Due to the relatively low number of existing facilities we felt it would be best to include all facilities (the entire population) in our sample to best achieve a representative response. Because C&D debris recycling is regulated at the state level and there are varying degrees of C&D debris recycling activity in each state we felt it was important to obtain responses from each state for a more representative sample. But not all states have C&D debris recycling facilities.

Survey Design

Facilities had the option to reply by mail (hard copy) or complete the survey online. Questions that were asked ranged from facility demographic characteristics relating to tons accepted, materials accepted, the number of employees, and tipping fees. There were also a set of technical questions relating to C&D debris fines, these questions included how they were managed, whether they were sent to a landfill for daily cover, who paid for the management and whether the fines were tested and how often. Also a question was asked regarding whether the facility was aware of H₂S problems from their C&D debris fines, and if so, what steps the facility had taken to alleviate the problem.

A preliminary list of questions had been formulated between the Department of Civil and Environmental Engineering and the Department of Resource Economics and
Development. Some questions and ideas were discussed with a C&D debris recycler to confirm ability to answer. For instance, we wanted to gain a better understanding of labor and mechanical intensity and how to measure it in the survey. We found it would be best to ask the number of employees and what some of the technological sorting procedures that were used at facilities. The initial list of questions was considerably long. With discussion we decided to eliminate some of the questions to potentially increase the likelihood of participation. The survey is included in Appendix A of this thesis.

The survey method followed a modified Dillman Tailored Design Method (2000). Initially, a letter was sent to facilities to introduce them to the survey and to make them aware that a survey would soon be arriving in the mail. Two weeks later the survey was mailed followed by a reminder postcard. Thirty facilities responded to this first-wave by mail and four responded online. Two weeks later a second mailing of the survey was sent to all facilities that had yet not responded. Eight more facilities responded by mail and one responded online, which increased the response to 43 facilities. Phone follow-ups were conducted to reach facilities that were either suspected to handle a large tonnage of material or were located in geographical regions with low response rates. During the phone follow-ups five more facilities responded online, one completed the survey over the phone, and two returned hard copies. A total of 40 facilities either returned the survey indicating that the facility was not a mixed recycling processor or the address was incorrect and returned by the postal service or confirmed it over the phone. The final response rate was 22 % with a total of 51 mixed C&D recycling facilities responding.

**Data Analysis**
In this thesis the US is divided into four regions. The Midwest is represented by the states of Illinois, Indiana, Michigan, Minnesota, and Ohio. The Northeast is represented by the states of Connecticut, Maine, Massachusetts, New Hampshire, New York, and Rhode Island. The South is represented by the states of Arkansas, Florida, Maryland, North Carolina, Oklahoma, Tennessee, and Virginia. The West is represented by the states of California, Iowa, Nevada, Oregon, Utah, and Washington. The states that are omitted either did not have any C&D debris recycling facilities that were located or did not have any respondents to the survey.

The survey responses were entered into a database. Each facility’s response was recorded for each question. After the closing of the survey all observations were double checked for accurate entry into the database. Descriptive statistics were used to analyze the data. Statistics were mostly limited to descriptive due to the low number of observations and the occurrence of item non-response. Most descriptions are mean, median, and mode. Some questions and their correlations were analyzed.

Question number six asked what the percentage of the total incoming feedstock was comprised of the given material types (demolition drywall, clean drywall, concrete, etc.) some respondents combined demolition drywall and clean drywall, or clean wood and demolition wood. These responses omitted from the final analysis and averages. Question number six also allowed respondents to fill in other materials that may be accepted their facility. Most respondents did not fill in any materials because there were so few filled in responses they were not included in the summary of the survey findings.

Questions fourteen, twenty, twenty five, and thirty were open ended responses. Question fourteen asked respondents that had experienced issues with H₂S generation
that was serious enough to prompt mitigation, what techniques they utilized to mitigate the \( \text{H}_2\text{S} \) generation from their C&D debris fines. Question twenty asked respondents why government had delayed operations. Question twenty five asked what policy recommendations respondents would make to increase the amount of C&D debris recycled. And question thirty asked what material the respondent currently feels is most problematic to manage and what material they feel will be most problematic in the future. The three questions were categorized based on general themes of the responses and then analyzed.

Question number seven asked respondents what the end uses and markets were that the incoming material types were used as. Most responses for each material type were categorized and had more than one respondent report that use. However, there were some uses that were only reported by one respondent. To maintain facility confidentiality the uses that were only reported by one respondent were categorized under “other”.

Facilities were asked how many tons are annually accepted at the facility; how many tons the facility is permitted to accept; and what is the facility’s tipping fee per ton. Some facilities responded in cubic yards rather than in tons. To convert cubic yards to pounds a rate of 484 pounds per cubic yard of C&D debris was used (Townsend, 2000).

Question thirty two asked respondents to delineate the geographic market area where approximately 75% of their total incoming feedstock came from. Two concentric circles were outlined around an ‘X’. The ‘X’ represented the recycling facility and the inner circle around represented a 50 mile radius around the facility and the outer circle represented a 100 mile radius around the facility. This question was not analyzed for this
thesis; however, will be of use for future research projects. It should be noted the respondent’s did seem to be able to accurately estimate their market areas.

Other questions were individually analyzed. Descriptive statistics including mean, median, and modes were found for most of the data. Analysis was based on regional location, facility size, materials, and state regulatory considerations as appropriate. All facility specific data is confidential.

**Anticipated Findings**

We did not anticipate that we would have a high response rate. There were a few variables that we knew would decrease our response rate. The first because we were targeting facility managers of facilities that do not require permitting in all states, simply locating the existing facilities was challenging. Secondly, because we were targeting industry individuals who we did not know many of their names, or at which company location they may work out of, it was difficult to ensure that the proper employee received the survey. Third, we knew that some general managers and/or the company they represented may not feel comfortable releasing proprietor information that they may prefer to keep confidential. Finally, because we were targeting general managers of facilities they may be busy and not have the time to complete the survey.

We anticipated finding that there would be a high degree of variability due to the lack of consistency in state regulations. Also geographic characteristics and waste stream compositions due to geographically dependent building characteristics would increase variability in our findings.
The following chapter will be a literature review. The existing research, data, and management recommendations are going to be presented and integrated into the new data obtained to formulate further recommendations for C&D debris management and policy.
CHAPTER THREE

LITERATURE REVIEW

C&D Debris Quantity and Composition

Construction and demolition (C&D) debris is a solid waste stream that is generated from the construction, demolition and renovation of buildings, bridges and roads. Until recently the quantity and characteristics of the C&D debris waste stream has been bypassed as critical to monitor, quantify, and regulate. The federal government mandates that state governments are responsible for defining, regulating, enforcing, and monitoring the C&D debris waste stream. Due to the lack of consistent definitions and state participation in monitoring it has been difficult to quantify the amount generated in the US. Typically C&D debris waste definitions include waste produced from the construction, renovation, and demolition of buildings, roads and bridges. C&D debris waste materials typically include wood, concrete, brick, asphalt, metals, gypsum drywall and roofing. Some states include yard wastes such as stumps, dirt, and rocks in their definitions (US EPA, 1998a; US EPA 2008a; Clark et al. 2006).

The US EPA in 1998 made the first attempt to quantify, the composition, generalize management across the US. The report focuses on building related C&D debris (excluding debris generated from bridges and roads) as this thesis will also focus on building-related debris. In 2008, the EPA conducted an updated report. These two EPA reports are the only two national quantification attempts. The literature available on the C&D debris waste stream is very limited.
In 1996 the US EPA (1998) estimated that 136 million tons of building-related C&D debris was generated in the US. There were an estimated 210 million tons of municipal solid waste (MSW) generated in that same year. The quantity of C&D debris, that prior was virtually unknown, prompted research and focus to reduce the waste, increase recycling, and ensure proper management techniques. The US EPA (2008) estimates 164 million tons of C&D related debris were generated in 2003 in the US.

Relatively recently it has become more common for states to distinguish between MSW and C&D debris waste streams in management requirements. The C&D debris waste stream is composed of materials which are chemically and physically different than MSW, therefore necessitating its unique management requirements (Clark, et al. 2006).

Not only is C&D debris different than MSW but construction debris is different than demolition debris and can be differentiated into two different waste streams. The ease of separation, compositional characteristics, recovery and recyclability differ for waste generated at a construction site and waste generated at a demolition site (Falk and McKeever, 2004).

The composition of the C&D debris waste stream is a function of the activity generating the waste (Cochran, 2006; US EPA 1998; US EPA, 2006). The C&D debris waste stream composition has not and likely will not change very much over time because the materials used in buildings have remained relatively constant from year to year. Wood is the most common material at construction and renovation sites, while, concrete is the most common component at demolition sites (US EPA, 2008).
Areas that are growing fast are likely to have construction and renovation debris dominating the C&D debris waste stream. However, more urban areas where old buildings are demolished for new development are likely to have more demolition debris in the waste stream (U.S. EPA, 2008). The C&D debris waste stream composition varies greatly from region to region across the US due to the use of different building materials in different regions (Tellus Institute, 2002).

Compositional generalizations by building type have been made. Residential buildings generate approximately 40% wood whether from construction, demolition, or renovation activities. Drywall accounts for approximately 20% of the waste from residential new construction and renovation. Roofing materials account for 25% of the waste from residential renovation and less for new construction and demolition. Concrete and asphalt amounts increase for residential demolition because of the inclusion of foundations and driveways. Non-residential buildings are even more difficult to generalize material composition because of the inconsistency in building types (Tellus Institute, 2002).

It is difficult to quantify the amount of C&D debris generated due to the lack of consistent C&D debris definitions across states, non-specific reporting mechanisms, and double counting between the C&D debris and MSW streams. Double counting occurs because MSW can be present at sites where C&D debris is generated (i.e., plastic bottles, paper, etc.) and households conducting renovation often will dispose of the renovation debris in MSW landfills rather than C&D debris landfills. Accurately estimating the waste stream when there is double counting is difficult (US EPA, 2008a).
Difficulties and inabilities in estimating the C&D debris waste stream not only make policy implementation difficult, it is also difficult to know the potential of waste materials as inputs for production processes. It is necessary to have accurate information on the amounts, location and availability of the waste material (Yost and Halstead, 1995; Cochran et al. 2007b). Cochran et al. (2007b) conducted a case study for estimating the amount of C&D debris generated in Florida suggestions that regional estimation is necessary for accurate estimation and that the methodology implemented should be practiced across the US.

Some nationwide estimates for quantities of materials specific to C&D debris have been conducted. In 2004 Falk and McKeever estimated 12 million metric tons of wood were generated in 2002, with less than 10% recycled or composted, 22% used as biofuel, and the remainder disposed. Cochran (2006) also used existing data to quantify the amount of drywall, wood, asphalt shingles, and concrete waste generated in the US. The purpose was to predict if current market demands could utilize these materials for recycling. It was found that for concrete states that do not produce natural crushed stone would likely have the most success with recycled crushed stone markets. Wood reuse for incineration would likely be most successful in Maine, California, Georgia, and Louisiana. While wood reuse as mulch can potentially be developed in all states; however, it has minimal demand opportunity and there is concern about contamination from CCA-treated wood that can leach arsenic into household groundwater supplies. Successful recycling markets for gypsum are likely limited to the states of California, Iowa, Illinois, and Indiana. It was concluded that asphalt shingle recycling market capacity is not existent but there may be potential for development (Cochran, 2006).
The best way to reduce the amount of waste disposed in landfills is to minimize the amount of waste generated. One way to do so is to design buildings in such a way to reduce the amount of building materials wasted during construction. A survey of architects by Osmani et al. (2007) on attitudes of building architects in the United Kingdom showed that architects were reluctant to adopt waste minimizing designs; likely due to lack of understanding of what creates design waste and assuming that waste minimization is the building contractor’s responsibility. The respondents were in support of rewarding implementation waste minimization strategies by government. Even if zero waste was generated at construction sites there would still be a significant amount of C&D debris generated through demolition and renovation.

**C&D Debris Disposal**

**Landfills**

C&D debris is most predominantly landfilled; however, recycling is becoming more common (Clark et al. 2006). It is estimated that 65-75% of the C&D debris generated in 2003 was land disposed either in C&D debris landfills, MSW landfills or unpermitted sites (US EPA, 2008). C&D debris material tends to be bulky and is estimated to take up 25-40% of landfill space (US EPA, 1998).

Because of the long-believed inert (not readily reactive with other elements) nature of C&D debris, many states do not have stringent regulations for C&D debris landfills. Clark et al. (2006) conducted a survey of state agencies responsible for C&D debris landfill regulation. The survey found that twenty seven states do not require C&D debris landfills to have liners. Groundwater monitoring varies widely in state regulation and is not dependent on a particular state’s liner requirements for C&D debris landfills.
Nineteen states that do not require liners also do not require groundwater monitoring, while nineteen of the states that require liners also require groundwater monitoring (Clark et al. 2006).

It has been found that C&D debris landfill leachate can contaminate groundwater. The Florida Center for Solid and Hazardous Waste Management conducted leaching experiments to simulate C&D debris waste leachate. It was found that the leachate exceeded the secondary maximum contaminant levels for drinking water in TDS and sulfate levels from the gypsum wallboard present in the waste stream (Townsend, 1998). Also, it was found that the leachate resulting from residential construction debris disposed in unlined landfills exceeded water quality standard levels for metals including iron, arsenic, aluminum, manganese and chromium (Weber et al. 2002).

It had long been thought that the relatively inert nature of C&D debris components meant C&D debris landfills would generate little or no biogas, unlike MSW landfills (Flynn, 1998). However it is common that H$_2$S generation at C&D debris landfills does occur (Johnson, 1986; Lee et al. 2006). H$_2$S gas has an odor similar to that of rotten eggs, commonly leading to public complaints about the smell. However, H$_2$S gas causes more problems than just an unpleasant odor; it has been found to have adverse health effects on humans. Workers and residents exposed to H$_2$S from a refinery complained of nausea, headaches, vomiting, difficulty breathing, nosebleeds, depression, and personality changes (Kilburn and Warshaw, 1995) and may also cause environmental problems. Eun et al. (2007) conducted a study to estimate the amount of variation in H$_2$S emissions using a flux chamber method at five C&D debris landfills in Central Florida, concluding that H$_2$S emissions varied spatially across specific C&D debris landfills. H$_2$S
odor is detectable at a concentration level of approximately 0.5 ppb and can cause unconsciousness and death at approximately 500 ppb (Flynn, 1998). Lee et al. (2006) found H₂S levels as high as 12,000 ppb at some landfills studied. MSW landfills also have problems with hydrogen sulfide formation. MSW landfills that receive C&D debris waste have much higher H₂S emissions than landfills that do not accept C&D debris (H₂S policy).

Materials painted with lead-based paint are commonly disposed in landfills. Recycling of such materials is difficult because the presence of lead based paint will deteriorate the quality of the product. A study conducted to measure the leach-ability of lead from lead-based paint in landfill environments using the toxicity characteristic leaching procedure (TCLP) and the synthetic precipitation leaching procedure (SPLP). The study found that concrete reduced lead leachability more than wood, steel, and drywall. It was recommended that more work needs to be done to assess lead leachability within an actual landfill environment, which can differ significantly from a simulated landfill (Wadanambi et al. 2008).

**Tipping Fees**

Tipping fee prices in the Northeast are so high that it is economically feasible for waste generators in Northeastern states to export C&D debris to Ohio where landfill tipping fees are significantly less. Ohio estimates that 40% of the total 8.3 million cubic yards of C&D debris waste landfilled in Ohio comes from out of state, mostly New York (Ohio Environmental Protection Agency, 2003). Ohio, which imports waste from many higher cost disposal states, is becoming more concerned with the effects C&D debris landfills have on environmental and human health (Cochran, 2004).
C&D debris landfills have relatively lower tipping fees than MSW landfills. Due to the generally inert nature of C&D debris, it is perceived that there is less risk of environmental pollution from C&D debris landfills. Thus, many states do not require leachate collection systems, liners and groundwater monitoring. The lack of requirements reduces the cost of landfill construction and operation, therefore allowing for lower tipping fees (US EPA, 2008; Clark et al. 2006). Disposal consumers will choose the least cost method of disposal; in areas where landfill tipping fees are especially low, high investment C&D debris recycling facilities will not be able to compete with landfill tipping fees.

**Recycling**

Recycling not only is usually beneficial for our environment, it also provides an opportunity for economic growth and development that unlike most traditional growth and development cases the demand on natural resources. The US EPA in a national joint effort conducted a study on the entire recycling industry in the US, including collection, hauling, processing and reuse and remanufacturing establishments, to quantify the impact recycling has on our economy. The study, titled “The US Recycling Economic Information Study” (US REI Study) found that the recycling industry is significant when compared to other industries supplying a large number of jobs that pay above the average national wage (RW Beck, 2001).

The recycling industry sector is larger than the landfill sector by providing more jobs that, on average, pay more than waste management jobs and the national average for all other jobs; even though there are more wastes discarded and not recycled than waste that is recycled. This is because recycling is a value-adding process for material that has
negative value (people pay to get rid of it) and is transformed into a material or product which is demanded (RW Beck, Inc, 2001).

A large portion of the C&D debris can be recycled; however, only a fraction of potentially recyclable material is actually recycled (Tellus Institute, 2003; Cochran et al. 2006; US EPA 1998; US EPA 2008a). It is estimated that approximately 20-30% was recovered for recycling in 1996 and approximately the same amount was recovered for recycling in 2003. Concrete, asphalt, metals, and wood are the most commonly recovered materials for recycling from the C&D debris waste stream (US EPA, 1998; US EPA 2008a).


Similar C&D debris recycling barriers and management problems are being faced internationally. In Hong Kong a survey conducted on C&D debris recyclers found that impurities in the incoming feedstock are a major issue and most facilities require materials to be sorted to avoid contamination (Tam and Tam, 2005). Lack of landfill space in Greece is prompting research to promote sustainable waste management including reuse and recycling (Fatte, 2003).

The highest recycling rates in the fastest growing states in the US are in New York and Massachusetts (Cochran, 2004). This is likely due to the Northeast region’s characteristic of having the highest landfill tipping fees in the US making recycling economically feasible.

C&D debris recycling facilities require a high initial investment and accept a large quantity of low valued material. The process of sorting C&D debris is mechanically and labor intensive making it costly. Also, some material must be disposed in a landfill which costs the recycler money. Without proper markets, incentives, and investments it is not feasible for a C&D debris recycler to operate. Risk of product contamination is a concern for recyclers due to the presence of asbestos, lead, mercury, and other hazardous materials that may be present in a building at time of demolition. These conditions make mixed material C&D debris recycling facilities difficult to open and operate.

Construction wastes are cleaner than demolition wastes and are therefore easier to recycle (US EPA, 2008). It is recommended that hazardous materials be removed from a building prior to demolition; however, often it does not occur (Townsend et al. 2004).
Demolition wastes and presence of hazardous materials cause successful operation and clean outgoing products for recycling facilities to be difficult.

To determine if recycling was the best management method for C&D debris, Cochran (2006) conducted a life cycle assessment to determine if recycling wood, concrete, asphalt shingles, and drywall created the fewest environmental impacts, or if landfilling, and incineration (without energy recovery) methods had less environmental impact. It was found that wood incinerated for electricity and the ash disposed in a lined landfill is the most desirable management method for wood. The least negative environmental impacts for the management of concrete, asphalt shingles and drywall are recycling.

**Source Separation and Deconstruction**

Source separation is when C&D debris is sorted on the construction site by material type. This is helpful for recyclability; reducing cost of separation for the recycler and reducing risk of contamination. However, source separation is very costly to building contractors and typically results in a net loss to the contractor because labor costs are so high and the lack of revenue from the separated material (Wang et al. 2004). Source separation also requires space to separate materials and in dense urban settings is very difficult if not infeasible.

Deconstruction is a practice where a building is selectively dismantled and materials are sorted on the job site. The practice of deconstruction provides economic and environmental benefits not available with the practice of demolition (Dentata et al. 2005). Deconstruction is ideal to eliminate the need for sorting of materials, which not
only reduces the cost of processing (sorting) materials, but also increases the quality of the recycled materials (US EPA, 2008a).

The cost of deconstruction can vary due to contractor experience in deconstruction and current market conditions. Dentata et al. in 2005 analyzed the economic considerations of deconstruction in Massachusetts. However, deconstruction takes more time and labor to complete than demolition increasing the cost, and the results showed that in Massachusetts deconstruction costs could be approximately 17% - 25% higher than demolition costs. However, increased training and knowledge of deconstruction contractors could decrease the cost. Costs of deconstruction will vary by regional economic characteristics.

**Recycling Markets**

Cochran (2006) conducted the first study to determine if substantial markets currently exist in the US for concrete, wood drywall, and asphalt shingles. Factors contributing to market existence included competition from virgin natural resources and from other recycled products. Also, market capacity for recycled materials and the amount of C&D debris waste generated were compared. It was found that states with the greatest potential for wood incineration are Alabama, Maine, California, Georgia and Louisiana (Cochran, 2006). Locations where asphalt shingle recycling might be successful include: California, New York, and Texas (Cochran, 2006).

Without stable markets for recycled material it would not be feasible for a recycler to operate. Currently, more stable markets are needed for gypsum drywall, asphalt shingles, and carpets (Wang et al. 2004). Drywall and asphalt shingles have a
significant market demand shortage for successful recycling opportunity (Cochran, 2006).

**Problematic Materials**

**Demolition Drywall**

Drywall is a difficult material to successfully recycle. Drywall consists of 85% (by weight) of gypsum that is between two layers of paper (15% by weight) (Townsend et al. 2001). Currently, demolition drywall has virtually no markets for recycling and construction (clean) drywall has very limited opportunity. Gypsum is not suitable for incineration because the sulfur dioxide gas produced when incinerated reduces the ability of the scrubbers to remove other acidic gases thereby reducing air quality (Marvin, 2000).

**Demolition Wood**

Demolition wood may be painted (possibly lead based paint) have nails, other compounds, and may be treated which make it more difficult to recover and recycle (Falk and McKeever, 2004). Some types of treated wood that may be present in the C&D debris waste stream include: acid copper chromate (ACC), alkaline copper quat (ACQ), ammoniacal copper citrate (CC), copper azole (CBA-A and CA-B), and copper Dimethylthiuram disulfide (DMDT) (US Forest Service, 2008). Although there are these different types of treated wood that need to be managed; copper chromated arsenate (CCA)-treated wood is probably the most researched and problematic type of treated wood in the C&D debris waste stream. CCA-treated wood is exempt from hazardous waste classification by the federal government even though the wood has characteristics of hazardous waste (Jambeck et al. 2007; US EPA, 2003). Although there has been a
phase out of residential uses CCA-treated wood in 2004 it will be in the US waste stream for many years to come (US EPA, 2002).

Recycling of CCA-treated wood is very limited due to the presence of chromium and arsenic; it is not recommended for use as landscaping mulch (Townsend et al. 2003; Solo Gabriele et al. 2004). When CCA-treated wood is incinerated arsenic emissions must be captured to maintain air quality standards. Chromium oxidation during incineration creates a more toxic and mobile form of chromium; the ash leftover from incineration is also contaminated with arsenic, copper and chromium and making management and disposal of the ash difficult (Solo-Gabriel et al. 2002; Iida et al. 2004; Song et al. 2006).

With little opportunity for recycling of CCA-treated wood, land disposal often occurs and 54% of US C&D debris landfills do not require bottom liners resulting in leachate permeating into the ground and possibly groundwater (Clark et al. 2006; Jambeck et al. 2007; Saxe et al. 2008; Saxe et al. 2007; Solo-Gabriele et al. 2007; Townsend et al. 2004b). CCA-treated wood is likely the cause of high levels of arsenic in leachate collected from unlined C&D debris landfills (Weber et al. 2002). Research conducted to determine the risk and levels of arsenic and chromium concentrations leaching from CCA-treated wood waste in unlined C&D debris landfill has conflicting conclusions. Townsend et al. 2004, Solo-Gabriele et al. (2007), Kahn et al. (2007) and Jambeck et al. (2007) have concluded that leaching of arsenic from C&D debris landfills has the potential to negatively impact groundwater over time and is cause for concern. Saxe et al. (2007; 2008) conclude that currently leaching of arsenic into groundwater (in
Florida) is not definitely caused by CCA-treated wood and more stringent hazardous waste regulations requiring more stringent disposal requirements is not necessary.

Jambeck et al. (2007) conducted a life cycle assessment of the tradeoffs between landfilling and incinerating CCA-treated wood. It was found that there were management and environmental tradeoffs between the management activities. Recommendations were dependent on whether or not the final landfill disposal site of either ashes (of incinerated CCA-treated wood) or the wood itself depended on whether the landfill was lined and leachate collected.

One problem with recycling non-CCA treated wood is the presence of CCA-treated wood and the difficulty distinguishing between the two types in the facility's sorting process. If CCA-treated wood is not removed it can contaminate non-CCA-treated wood products. In the case of incineration CCA-treated wood presence can potentially exceed US allowable levels (Jacobi et al. 2007). Landscaping mulch is another common end-use for recovered wood. Contamination of CCA-treated wood in landscaping mulch can cause arsenic and chromium levels to exceed regulatory thresholds as well (Tolaymat et al. 2000; Jacobi et al. 2007b).

Jacobi et al. (2007a) and Solo-Gabriele et al. (2004) have conducted studies to identify cost effective methods for sorting treated wood from non-treated wood at recycling facilities. Source separated loads can quite accurately minimize contamination of treated wood by visual inspection, since deconstruction and source separation can be very costly it is not the predominant method for building take-down (Dentata et al. 2005). Most mixed material C&D debris recycling facilities accept commingled loads. It is more difficult to minimize treated wood contamination in commingled loads, sorting
using a hand-held X-ray fluorescence (XRF) was found minimize contamination; however, is currently not economically practical (Jacobi et al. 2007a). The study conducted by Solo-Gabriele et al. (2004) evaluated both the XRF hand scanners and a laser induced breakdown spectroscopy (LIBS). It was found that although the XRF hand scanners accurately detected CCA-treated wood in different conditions (wet, painted, rotted, etc.) it was not designed for on-line operation. The LIBS system effectively identified CCA-treated wood and was also capable of identifying wood that was painted and stained. However, the study concluded that an increased labor pulse would be necessary to identify wood of varying thicknesses, wet wood, and rotted pieces of wood accurately. Solo-Gabriele et al. (2004) found that both technologies have potential with more research and development to provide recycling facilities with a means to sort treated wood from non-treated wood.

CCA-treated wood may currently not have much recycle value; however, current research is attempting to remove the metals within the wood for recycling. This practice would require storage and CCA-treated wood until quantities become large enough for feasible metals recovery. After metals were recovered from the treated wood it would become available for biofuel energy and eliminate the concerns about air quality degradation and heavy metals in the ash. However, if exposed to precipitation, the leachate generated from such a stockpile would likely be a hazardous waste and would require a hazardous waste generator facility classification or treatment storage and disposal (TSD) facility in the US. To avoid leachate generation, the wood could be stored and covered (Jambeck et al. 2006a)

C&D Debris Fines
C&D debris fines are a byproduct of the sorting process. Truckloads of commingled material are dumped on a tipping floor in a recycling facility and sorted by material type. At the end of the processing line the final materials are screened (using variable sized screens) resulting in a soil-like material known as C&D debris fines. C&D debris fines generally are composed of small pieces of gypsum drywall, wood, concrete, brick, asphalt, paper, and plastic. The actual composition of the C&D debris fines is a function of the sorting process utilized by a facility and the materials delivered to the facility (Townsend et al. 2004).

C&D debris fines typically have a high proportion of gypsum wallboard which is composed of sulfate and water. A landfill is an anaerobic environment in which bacteria will reduce the sulfate and emit hydrogen sulfide and carbon dioxide gases. Hydrogen sulfide is colorless and flammable. Hydrogen sulfide emissions are not only a nuisance because of the unpleasant odor but more important can be a health hazard in very low concentrations. The odor is detectable at 0.5 ppm, and at concentrations greater than 500 ppm can result in loss of consciousness and death without warning due to loss of olfactory senses at levels higher than 100 ppm. The rate of hydrogen sulfide generation depends on the amount of organic matter, concentration of dissolved oxygen in the leaching solution, the temperature, and the pH (Jambeck et al. 2006).

C&D debris fines are the largest (by mass) outgoing material from mixed C&D debris recycling facilities (Townsend et al. 2004). Mixed material C&D debris recycling facilities must find the least cost regulatory permissible markets to dispose of C&D debris fines (Musson et al. 2007). Fines management outlets are mostly limited to landfill use as ADC and shaping and grading; or they are dumped in a landfill and not
used as ADC. The gypsum concentrations in C&D debris fines can cause hydrogen sulfide formation when they are used in MSW landfills as an alternative daily cover.

The concentration of gypsum in C&D debris fines impacts the level of H$_2$S formation. Musson et al. (2007) developed a standard operating procedure (SOP) for measuring the gypsum content in C&D debris fines. The SOP developed is simple enough to be performed by most environmental analytical laboratories, provide consistent results, is cost effective and rapid.

Jang and Townsend (2001b) conducted a study to measure sulfate levels in leachate from C&D debris fines. Drinking water with high levels of sulfate can have the odor of rotten eggs and cause diarrhea (especially in infants and transients). The US EPA considers it a secondary pollutant (US EPA, 2008a). Jang and Townsend (2001b) tested multiple batches of C&D debris fines that had approximately 1.5% to 9.1% gypsum (by mass) and found that the levels of sulfate leaching from C&D debris fines exceeded the secondary drinking water standard for sulfate. Site specific hydrogeology and state and local regulations for secondary standards in groundwater should be considered prior to land application of C&D debris fines.

Another study by Townsend et al. (2004) evaluated the heavy metals in C&D debris fines. Arsenic levels were most frequently found to exceed the risk-based target levels. They concluded that reuse in land application should be limited and is not recommended for residential land application. Jang and Townsend (2001a) also found that levels of organic pollutants are not a human health concern.

**C&D Debris Policy**

**Current Policy**
The federal government leaves states to define, implement and enforce regulations on the C&D debris waste stream. However, the federal government does regulate hazardous substances which may be present in the C&D debris waste stream. Several federal statutes affect the way C&D debris is managed; these statutes include the Resource Conservation Recovery Act, the Toxic Substances Control Act (TSCA) and the National Emission Standards for Hazardous Air Pollutants (NESHAP). These statutes make C&D debris generators strictly liable for any hazardous waste that they may dispose (Clark et al. 2006).

There are many different types and degrees of C&D debris regulation being practiced across the country. Clark et al. (2006) surveyed and reviewed state regulations regarding the C&D debris waste stream. State regulation still focuses primarily on land disposal of C&D debris. Twenty three states had specific C&D debris disposal regulations in 2006, while the other twenty seven states included C&D debris under requirements for inert debris landfills, non-MSW landfills, MSW landfills or general solid waste facilities. States’ definitions of C&D debris varied widely across the US. Clark et al. concluded that the variation in regulations across states was result of unique characteristics in each state including environmental (i.e., rainfall, temperature, land availability, geologic stability), political (i.e., perceptions of the significance of waste policy and the risk to human and environmental health) and economic variations. The lack of consistency for liner and groundwater monitoring requirements by states indicates that states may be unclear about environmental risks associated with C&D debris disposal in landfills.
States and localities are implementing direct regulation, market incentives, and education; these three techniques are applied in different ways and in varying degrees. Many states have provided grants and developed guidelines for recycling program implementation. Cochran et al. (2004) evaluated different approaches, their costs, and the impact (degree of increased recycling) the different approaches had on recycling.

Market incentives include disposal taxes, subsidized recycling, business development, and advance disposal fees/deposits/rebates which all decrease the cost of recycling. Deposits and advanced disposal fees and rebates often will result in revenues to the city or county because the contractor will pass the advanced costs on to the customer who often does not return to claim the reimbursement. Demolition contractors on the other hand will use the program and receive significant returns. This category of regulation has, on average the lowest cost per tons recycled and has been found to increase recycling rates significantly (Cochran, 2004).

Direct regulations may include disposal controls including taxes and bans, recycling requirements, green building requirements, recycling goals, and salvage requirements. Recycling goals have had little success in increasing recycling. Green building requirements are usually imposed on city and county buildings, these buildings not only recycle construction materials they often utilize recycled content products in the building construction (Cochran, 2004; USGBC, 2008). Policy requiring C&D debris landfill liners can make recycling more economically feasible (Cochran et al. 2004; Clark et al. 2006) and potentially increasing recycling rates.

The state of Massachusetts has implemented a waste ban on the landfilling of certain C&D debris materials to reduce land disposal and increase recycling. The Tellus
Institute (2002) conducted an evaluation with recommendations for strategies which could help decrease waste (of all kinds, including C&D) and increase recycling in Massachusetts. Massachusetts has banned the landfilling of unprocessed wood, metal, asphalt, brick, and concrete; these materials account for 70% of the total C&D debris waste stream for the state. The ban is projected to increase the state’s C&D debris recycling rates significantly from 80% in 2000 to 88% in 2010 and have only had a modest impact on source reduction. The state is currently considering implementing the waste ban to include gypsum wallboard and asphalt shingles, as long as successful end-use markets are established. One problem that Massachusetts is experiencing with the waste ban is the lack of enforcement. The Tellus Institute also recommended that the waste ban be accompanied by education and training for contractors, C&D debris processors, and disposal facilities.

**C&D Policy Considerations**

Clark et al. (2006) recommended that a federal definition of C&D debris would be beneficial to “facilitate research efforts and to address this issue in a uniform manner”, (page 182) suggesting that without a consistent definition of what the C&D debris waste stream is, it will be hard to quantify and recommend management practices.

Regulations require enforcement and monitoring to ensure that laws are being followed. Disposal restrictions require sufficient oversight to insure that the materials are not being landfilled, which can be costly. Recycling requirements also have enforcement issues to make sure that contractors are in fact recycling the material they say they are (Cochran, 2006). C&D debris management regulations that are implemented need to be
taken seriously by state, county and local officials, otherwise recycling rates will not be significantly increased (Cochran et al. 2004).

Prior to implementing regulations of any kind (i.e., market incentives, bans, deposits/refunds) the potential impacts of those regulations should be considered. Impacts considered should include those on C&D debris waste processors and construction contractors (Wang et al. 2004). Wang et al. (2004) developed a cost analysis model to be used in the decision making process of an integrated C&D debris waste management system. This tool can be used to quantify volumes of waste for specific regions and or projects and allows users to compare alternative management options for cost effectiveness.
SUMMARY OF THE SURVEY OF MIXED DEBRIS C&D RECYCLING FACILITIES

Introduction

A survey of C&D debris recycling facilities across the US was conducted to help illustrate the current industry practices to make better informed management recommendations. The data summarized are based on respondents and not on facilities. Some respondents operated more than one facility and combined multiple facilities into a single response. Some respondents did not complete all questions. Therefore analysis was based only on those responses completing the question.

Response Rate

The final response rate was 22% of the total population. Response rates were broken down by region; the Midwest had the highest response rate and the South had the lowest. Business surveys notoriously have low response rates, typically business response rates range from approximately 10-50% with an average around 21% (White and Luo, 2005; Tarnai and Paxson, 2004; Paxson et al. 1999). All conclusions and inferences from these data should be used knowing that there is the possibility of non-response bias. However, the survey targeted the facility managers who are busy and often are not spending work days in an office. Figure 1 shows the response rates broken down by region, the US response rate was 22%.
Participants reported the total tonnage accepted at their facility in the last year. The US EPA estimated that in 2003, 164 million tons of building-related C&D debris.

The total amount reported in this study was 4,248,713 tons which is 2.59% of the total estimated amount generated amount in 2003 (US EPA, 2008a). Forty four participants (19% of the total sample population) answered the question.

The average tonnage accepted per facility is 96,607 tons annually. Small facilities are delineated as those accepting 96,000 tons or less and large facilities are those accepting more than 96,000 tons. Twenty two respondents are small facilities and twenty two respondents are large. The remaining seven respondents did not answer the question. Figure 2 represents the percentage of facilities that accept different quantities of material annually. Most facilities accept between 100,000 and 149,000 tons annually.

Figure 1: Response Rates by Region

![Graph showing response rates by region](image)
The tonnage reported was also broken down by region and facility size. The south was represented by more small facilities, while the west had more large facilities. The Northeast and Midwest had similar numbers for each category.

Table 1 illustrates the mean, median and total annual incoming tons of respondents by region.
Table 1: Total Incoming Tons by Region

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<tr>
<td>Midwest</td>
<td>86184</td>
<td>60000</td>
<td>775653</td>
</tr>
<tr>
<td>Northeast</td>
<td>103571</td>
<td>100000</td>
<td>1448000</td>
</tr>
<tr>
<td>South</td>
<td>57473</td>
<td>68000</td>
<td>627260</td>
</tr>
<tr>
<td>West</td>
<td>127072</td>
<td>100000</td>
<td>1397800</td>
</tr>
<tr>
<td>US</td>
<td>96608</td>
<td>95000</td>
<td>4,248,713</td>
</tr>
</tbody>
</table>

Accepted Materials

Mixed material C&D debris recycling facilities may accept different materials for processing. These restrictions may be due to regional market demand for the processed materials and the facility’s processing procedure and technical capabilities. The respondents of the survey, on average, reported that they would accept 12 different materials. Figure 4 shows the most commonly accepted materials were construction wood, wood pallets, concrete, and metals (both non-ferrous and ferrous). The least commonly accepted materials were demolition drywall, carpet, and yard waste.

Figure 4: Percent of Respondents Accepting Material Types
It is suspected that demolition drywall is not accepted due to problems created in the C&D debris fines and lack of markets for the material. Demolition drywall can also pose environmental and human health risks due to lead paint, asbestos, and other toxic chemicals that may be present on the material. Therefore markets for the recycled demolition drywall products are virtually non-existent. Yard waste can be processed by landscapers and other businesses that have much lower operating costs than a C&D debris recycler, which may be why few C&D debris recyclers reported accepting it. Yard waste is also not typically included in state C&D debris definitions (Clark et al. 2006). Carpet also has very few recycling opportunities and so is often landfilled, which is costly to a recycler who has to pay for the disposal.

**Waste Stream Composition**

The US EPA has estimated the approximate percentages different materials make up of the C&D debris waste stream. Survey participants were asked to report the composition of their incoming waste stream. The US EPA and the survey participant averages were compared in Table 2. Table 3 shows the average percentage of materials that represent the C&D debris recycling waste stream nationally and regionally as reported by respondents.

<table>
<thead>
<tr>
<th></th>
<th>Survey Composition Average</th>
<th>EPA Composition Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drywall</td>
<td>12.77%</td>
<td>5 – 15%</td>
</tr>
<tr>
<td>Concrete</td>
<td>11.88%</td>
<td>40 - 50%</td>
</tr>
<tr>
<td>Shingles</td>
<td>8.56%</td>
<td>1 - 10%</td>
</tr>
<tr>
<td>Wood</td>
<td>47.42%</td>
<td>20 - 30%</td>
</tr>
<tr>
<td>Metals</td>
<td>8.95%</td>
<td>1 - 5%</td>
</tr>
<tr>
<td>Brick</td>
<td>3.07%</td>
<td>1 - 5%</td>
</tr>
</tbody>
</table>

*Table 2: Comparison of Respondent Composition and US EPA Composition of C&D debris waste stream (US EPA, 1998)*
The composition averages reported by facilities and that estimated by the US EPA are comparable. It is probable that the large difference in concrete estimates is because there are a few thousand recyclers that only recycle concrete; therefore, mixed material C&D debris facilities would not be accepting large quantities of concrete. Wood includes both new construction and demolition/treated wood and wood pallets and is not much higher than US EPA estimates. The survey found metal recycled to be twice the US EPA estimated percentage.

**Recycling Rates & Sustainability**

Recycling rate was defined to the respondent as the percentage of incoming material (of tons accepted) that is made into reusable product. Participants were asked to report their facility’s recycling rate (Table 4). The Midwest reported the highest average recycling rate.
Recycling Rates were also broken down by facility size (Table 5). Larger facilities tended to have higher recycling rates. This might be because the investment and capital for sophisticated sorting processes in a C&D debris recycling facility are quite high. Only facilities with high revenues would be able to afford the necessary equipment to have high recycling rates. Figure 5 illustrates the percentage of responding facilities’ recycling rates. Most facilities have recycling rates higher than 75%; however, there are a few facilities with very low recycling rates.

<table>
<thead>
<tr>
<th></th>
<th>Recycling Rate</th>
<th>Mean</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>Median</td>
</tr>
<tr>
<td>Midwest</td>
<td>77.22%</td>
<td>90.00%</td>
<td></td>
</tr>
<tr>
<td>Northeast</td>
<td>75.17%</td>
<td>82.50%</td>
<td></td>
</tr>
<tr>
<td>South</td>
<td>53.27%</td>
<td>50.00%</td>
<td></td>
</tr>
<tr>
<td>West</td>
<td>70.26%</td>
<td>80.00%</td>
<td></td>
</tr>
<tr>
<td>US</td>
<td>69.95%</td>
<td>77.00%</td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Recycling Rate by Region

Figure 5: Facility Recycling Rates

Sustainable building practices are becoming more mainstream. Some reasons for this include increasing energy costs, more awareness of environmental degradation due to
our built environment, and attention to poor indoor air quality caused by toxic chemicals and materials used in construction. Green building techniques include recycling construction and demolition debris from demolition sites and using recycled products in the building processes. Leadership in energy and environmental design (LEED) certified buildings utilize less toxic, recycled, and recyclable materials. LEED requires C&D debris to be minimized on the job site and managed in a sustainable and environmentally sound manner, including recycling.

Builders can earn points toward LEED certification if they recycle C&D debris. However, the builder must provide LEED with certification that the materials were in fact recycled. Participants were asked if they had the capability of tracking a client’s recycling rate and most respondents reported that they were capable of doing this and that they have done so in the past (Figure 6).

Figure 6: Ability to Track Client's Recycling Rate

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>4%</td>
<td>Yes, we have done this</td>
</tr>
<tr>
<td>4%</td>
<td>Yes, but we have not done this</td>
</tr>
<tr>
<td>14%</td>
<td>No</td>
</tr>
<tr>
<td>27%</td>
<td>I do not know</td>
</tr>
<tr>
<td>51%</td>
<td>Did not Respond</td>
</tr>
</tbody>
</table>

Processing

Each facility may have a unique procedure for handling the materials that come to their facility. Some facilities may be more labor intensive and some may be more
mechanically intensive. It was anticipated that the facilities that incorporate more diverse and technologically advanced mechanical processes will have higher recycling rates and be able to handle more materials.

Facilities were asked to indicate which procedures their facilities incorporated in their processing. Grinding, screening, magnets and hand picking were the most often utilized technologies incorporated into a facility’s sorting process. Eddy current separators, air classifiers, and float tanks were not as commonly used (Table 6).

Utilized processing was broken down by recycling rate and facility size. As expected, facilities with higher recycling rates had more mechanical and technically advanced sorting procedures than those facilities with lower recycling rates (Table 7). Processing procedures were also compared for small facilities (those accepting less than 96,000 tons) and large facilities. As would be expected smaller facilities had less capital invested in more technically advanced mechanical sorting processes.

<table>
<thead>
<tr>
<th>Sorting Process by Recycling Rate</th>
<th>70% or Less</th>
<th>Greater than 70%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnets</td>
<td>63%</td>
<td>81%</td>
</tr>
<tr>
<td>2nd Magnet Type</td>
<td>21%</td>
<td>23%</td>
</tr>
<tr>
<td>3rd Magnet Type</td>
<td>0%</td>
<td>4%</td>
</tr>
<tr>
<td>Eddy Current</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>Grinding</td>
<td>54%</td>
<td>81%</td>
</tr>
<tr>
<td>Screening</td>
<td>3%</td>
<td>4%</td>
</tr>
<tr>
<td>Float Tank</td>
<td>0%</td>
<td>12%</td>
</tr>
<tr>
<td>Air Classifier</td>
<td>1%</td>
<td>15%</td>
</tr>
<tr>
<td>Picking Line (Average # Workers)</td>
<td>8</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 6: Sorting Processing by Recycling Rate
Facilities were asked to report the number of full-time workers and part-time workers employed. Fifty six facilities responded to question. There are 1,428 full-time jobs provided by these facilities and 122 part-time jobs.

Labor is another element of the sorting process. However, employees may not only be used for physical material handling, they may serve administrative roles as well. The average facility employs 28.5 full-time workers and 2.5 part-time workers. Larger facilities have an average of 41.18 full-time workers and 4.3 part-time workers. Smaller facilities have an average of 21.1 full-time workers and 1.5 part-time workers.

The number of employees was used to indicate the labor intensity of large and small facilities. Large facilities average .277 workers per one thousand tons accepted and small facilities average 2.94 workers per one thousand tons accepted. This suggests that small facilities may be more labor intensive because they have less technical capital intensive sorting procedures.

### On-site Landfill

Recycling facilities were asked if there is a C&D debris landfill or a MSW landfill on site. Only 6% of facilities reported having an MSW landfill, 4% had a C&D debris landfill.
landfill and 90% did not have an on-site landfill. A comparison of facilities with on-site landfills and recycling rates is provided in Table 8.

<table>
<thead>
<tr>
<th>On-Site Landfill and Recycling Rate</th>
<th>70% or Less</th>
<th>More than 70%</th>
</tr>
</thead>
<tbody>
<tr>
<td>C&amp;D</td>
<td>11%</td>
<td>4%</td>
</tr>
<tr>
<td>MSW</td>
<td>6%</td>
<td>7%</td>
</tr>
<tr>
<td>None</td>
<td>78%</td>
<td>89%</td>
</tr>
</tbody>
</table>

Table 8: Comparison of Facilities with On-site Landfills and Recycling Rate

While it appears facilities without on-site landfills have higher recycling rates, the sample size probably isn’t large enough to draw any firm conclusions.

**Landfill Collaboration**

Some landfills and recycling facilities actually collaborate for the interest of both parties. Landfills that receive C&D debris that could be recycled will divert the material to a recycling facility. Details of the contractual exchange were not asked of the participants. If collaboration took place, participants reported the approximate tons that were diverted from the landfill to recycling. We were led to expect that we would not find landfill and recycling facility collaboration. Most facilities did report that collaboration did not take place whether or not a landfill was nearby. However, 14% of landfills reported that their company also operated a landfill from which they diverted material to the recycling facility. Fourteen percent of facilities reported that they were currently trying to work out an agreement with a landfill to divert material from the landfill to recycling. And, 16% also reported that they did collaborate with landfills (not within their own company) to divert materials. On average facilities that were currently diverting material reported that approximately 24% of their annual tonnage came from the landfill collaboration.
Recycling Demand

Participants were asked what they believed were the main factors contributing to the demand for their facility's recycling services. Respondents were given five possible factors including: ease of access (location), population growth, natural disasters, growth and development, and policy. Respondents had the opportunity to fill in another factor they perceived to be a major contributor to demand. The most common filled in answer was Leadership in Energy and Environmental Design (LEED) certification for buildings (Figure 7).

Figure 7: Perceived Factors of Demand

![Bar chart showing perceived factors of demand]

In an effort to forecast the increasing demand for C&D debris recycling services, facilities were asked if they were planning to physically expand the size of their facility. Thirty percent of facilities answering this question reported that their facility was expecting to expand the physical size of their facility in the next year. This could be a positive indicator that facilities are experiencing increasing demand for their services and are expecting that, by increasing facility size, they may recycle more materials. Most of these facilities planning expansion are located in the West.
Material Final Disposition

Participants were asked to indicate the final disposition or end uses for the specified materials. Most materials have diverse opportunities for end uses. This could possibly signal more stability in the market for these materials. The charts in this section represent the reported final disposition and end uses for specific materials from their facilities. Some facilities did not report any uses and some facilities reported multiple uses for a single material. The 'other' category represents all uses which were reported by one respondent. Some materials were reported as being landfilled. Landfilling was not supposed to be included in a facility’s recycling rate as an end use.

Demolition drywall was recycled at a lower rate than clean drywall. This is likely due to the potential for hazardous materials and other components present on demolition drywall (Figures 8 and 9).

Figure 8: Demolition Drywall Final Disposition
Aggregates including concrete, brick, and asphalt were reported as being used for similar end uses. These uses were predominantly for road bases and recycled aggregates (Figures 10, 11, and 12).
Asphalt roofing shingles are a material that has geographically varying regulatory management requirements. For instance, in Massachusetts a landfill ban on roofing shingles currently is being considered. However, in Illinois recycling of shingles is not allowed. Not all states have asphalt pavement production and because asphalt shingles have the capability to be recycled into asphalt paving this may be one reason why there are so little recyclers able to recycle asphalt shingles (Cochran, 2006). And perhaps because of the regulatory variability across states there is lack of market development for
recycling. Roofing shingles are most commonly landfilled with a few facilities reporting other uses (Figure 13).

**Figure 13: Asphalt Shingle Final Disposition**

![Graph showing asphalt shingle final disposition](image)

Carpet is another material with little recycling opportunity and is mostly landfilled (Figure 14). Many facilities indicated that they would not accept carpet for this reason. However, there are companies such as New Frontiers Industries in Milton, New Hampshire, that are investigating and beginning to develop recycling opportunities and products from recovered carpet.

**Figure 14: Carpet Final Disposition**

![Graph showing carpet final disposition](image)
Demolition wood and clean wood had some similar uses (Figure 15 and 16); however, demolition wood has less opportunity for recycling. Demolition wood may contain CCA–treated wood and lead paint. These chemicals can leach and be potentially hazardous in landfill settings (Jambeck et al. 2005). When CCA-treated wood is burned, the ash may have high levels of these toxins, which will also ultimately end up in a landfill and be potential pollutants (Solo-Gabriele et al. 2002). Wood Pallet uses were similar to that of clean wood (Figure 17).

**Figure 15: Demolition Wood Final Disposition**

![Image of bar chart showing final disposition of demolition wood](image1)

**Figure 16: Construction Wood Final Disposition**

![Image of bar chart showing final disposition of construction wood](image2)
The high value of metals both ferrous and non-ferrous indicates that there seems to be little difficulty for facilities to market these materials. All facilities indicated that these materials were sold to metal brokers of some kind.

Although cardboard has one primary end use (paper products) the market for cardboard does appear to be stable given the current high demand for recycled paper products. Yard waste end uses were somewhat evenly distributed among different opportunities, as shown in Figure 19. However, many facilities reported that they will not accept yard waste.
Problematic Materials

Facilities were given the opportunity to describe any materials that they are currently having difficulties in managing or that they may be concerned about in the future and why. These may be materials that are brought to the recycling facility or may be produced by the recycling facility (e.g. C&D debris fines). Facilities most commonly reported that C&D debris fines were problematic (Figure 20). Some facilities reported that they had very limited disposal options, because landfills with whom they were
competing were unwilling to accept the fines. Many of these facilities said that if they were denied the ability to dispose/manage C&D debris fines in landfills due to changes in legislation their facility would have difficulty maintaining successful operations. It should be noted that the cover letter to the survey and a lengthy section in the survey dedicated to C&D debris fines may have initiated respondent’s thoughts on C&D debris fines.

Treated wood was another material that facilities were having difficulty handling. Some facilities were concerned with either current or changing legislation that would limit or prevent the ability to use treated wood as biofuel.

Some facilities were concerned with hazardous materials including asbestos, wood treated with lead based paint, and mercury in the waste stream. Some participants stated that these materials affected the quality standards and increased the cost of quality control for their materials.

**Figure 20: Reported Problematic Materials**

![Bar chart showing frequency of reported problematic materials](image-url)
Plastic was described as an issue because separation of plastic from the rest of the waste stream is difficult. Hazardous materials that were mentioned included asbestos, mercury, and contaminated soils. Biofuel was described as problematic due to the specifications for air quality given by state governments.

**C&D Debris Fines**

C&D debris fines management markets are mostly limited to landfill use as ADC and shaping and grading. Alternatively, they are dumped in a landfill and not used as ADC. Nearly all facilities reported that they had to pay a landfill to accept their C&D debris fines either for dumping or for use as ADC. Two respondents reported that the landfill would pay for the fines for use as ADC and one facility reported that they were able to discard the fines at the landfill for free. There were also three respondents who reported that they owned/operated a landfill; therefore, they did not have to pay, at least not explicitly, to discard their C&D debris fines. Nearly all facilities sending C&D debris fines to a landfill for all uses hauled the fines themselves. Only one facility reported that the landfill would haul the C&D debris fines.

When respondents were given the opportunity to identify any materials that they feel are problematic to manage, C&D debris fines was the most reported material, either due to current issues with disposal or concerns about future opportunities.

The final screen size used determines the approximate particle size of the C&D debris fines. The smaller the screen size, the less quantity of C&D debris fines to manage but typically there is a greater concentration of gypsum in the C&D debris fines; however, greater gypsum concentrations can increase the likelihood of H₂S formation. Larger screen size typically results in less concentrations of gypsum in the fines and less
likelihood for H₂S formation; however, there is a higher quantity of C&D debris fines to manage. There is a tradeoff between a higher quantity of C&D debris fines a smaller more concentrated amount; an optimum screen size to balance quantity and quality needs to be found. Participants were asked what the final screen size used in their process. Most facilities reported a two inch screen (Figure 21). All regions reported that use as ADC at landfills was most common (Figure 22).

Figure 21: Reported Final Screen Size
Facilities were asked if they have experienced H$_2$S formation from their C&D debris fines, and if so, what steps the facility has taken to mitigate the formation if the problem was serious enough. When the H$_2$S awareness question results were broken down by region, all regions most commonly reported that they did not have H$_2$S problems from their C&D debris fines.

Figure 23: Hydrogen Sulfide by Region
Facilities indicating that the H$_2$S formation was problematic enough to prompt mitigation reported that they had either required or recommended source separation of gypsum drywall, decreased the allowable amount of gypsum in a load, implemented a gypsum removal program, began composting clean drywall, or stopped allowing full gypsum loads. Some facilities reported taking steps to mitigate H$_2$S formation even though they reported they did not have H$_2$S formation.

It has been found that C&D debris fines not only may emit H$_2$S but also may contain toxic levels of heavy metals (Townsend et al. 2004a). Facilities were asked if they currently characterize their fines through analytical testing. Most facilities reported not testing the fines at all. Figure 25 represents the percentage of facilities which conduct tests on their C&D debris fines. When facilities did test frequency was most common at daily and monthly intervals.

![Figure 24: Percent of Facilities Testing](image)

**Siting**

Siting recycling operations can sometimes pose a burden to the facility operator because communities may oppose unpleasant, dirty, noisy operations. This is more
commonly known as the “Not in My Backyard” (NIMBY) attitude. A set of questions related to siting decisions and processes was included in the survey to help understand why a company will choose a particular location for processing operations. Facilities were asked if they experienced delays in siting their facility due to local, county, state or federal government intervention, illustrated by Figure 26. Twenty nine percent of respondents reported experiencing a delay in operations due to siting complications. Figure 27 shows the reason for government intervention in siting a facility. Siting complications and delays were most commonly brought about from community governments and state governments. The most common reasons for delay included: truck traffic, noise, dust and zoning issues. The average delay reported from government intervention was 10.5 months. This can be a substantial amount of time for a company with fixed investment costs and no revenue.

**Figure 25: Government Intervention of Facility Siting**
Importance of location characteristics, infrastructure, and tax structure were rated from not important, important, and very important by participants. Railway access and interstate access importance are likely due to the transportation modes utilized by the recycling facility’s clientele. Interstate access was most commonly reported as very important and railway access was most commonly viewed as not important to important. Rail can be a convenient and relatively inexpensive transportation mode; however, it has limitations. Interstate access is probably very important because most of the debris is transported by truck and trucks have the ability to reach more work sites directly as opposed to rail. Perhaps with increasing energy prices the importance of railway access will increase; however, the limitations of the railway and accessibility to job sites will likely keep the important of interstate access as more of a priority than railway access.

Local acceptance was most commonly viewed as very important to respondents. It may be that the recycling facility operators do not want to have difficult public relations that will increase the cost of operating and keeping a community happy.
Demand for recycling services was most commonly reported as very important, which is not surprising.

Local tax structure was most commonly viewed as not important to important. This may be because local taxes are limited to a property tax which marginally may not make a significant difference. State tax structure was most commonly viewed as important to very important. State taxes may be viewed as more important because state taxes can affect more diverse areas and operational factors for a recycler. Some of these factors may include: transportation costs, employee taxes, income tax, sales tax, etc, which may more significantly affect business success.

**Policy**

Participants were given the opportunity to volunteer what they would recommend to policy makers to help increase recycling. There were a few responses that may be classified as hostile toward their local and state governments and are probably due to frustration. Figure 27 shows a general classification of the recommendations provided. Most facilities felt that some mandate for recycling would effectively increase C&D debris recycling.

**Figure 27: Policy Recommendations**

![Policy Recommendations](image)
Tipping Fees

Recycling facility tipping fees are driven by the landfill tipping fee prices in a region. Regions with lower landfill tipping fees generally have more landfill space availability. In 2004, landfill tipping fees\textsuperscript{1} in the Northeast averaged approximately $70 per ton. In the Midwest (where population density is lower) the average tipping fees averaged approximately $35 per ton (Repa, 2005). The Northeast region has high tipping fees due to limited open space and the presence of NIMBY attitudes among residents and a higher demand for disposal.

Recycling facility tipping fees reported by participants reflected the landfill tipping fee prices. The Northeast had the highest average tipping fees of any region in the US.

Figure 28: C&D Debris Recycling Facility Tipping Fees

\textsuperscript{1} Recent C&D landfill tipping fee prices have not updated since 1994. MSW landfill tipping fees are used to show the comparison.
Conclusion

The data compiled from the survey give an illustration of the current C&D debris recycling industry. Considerations should be made when interpreting the data provided by the survey because of the low number of responses, geographic characteristics, and the diversity of state regulations. The information provided is intended to give a basic illustration of current C&D debris industry practices nation-wide.

Chapter five will use the data summarized here and other available data to provide some recommendations for policy and C&D debris management decisions. These recommendations are intended to help increase the volume of C&D debris recycled throughout the US.
CHAPTER FIVE

POLICY AND MANAGEMENT RECOMMENDATIONS

Policy for the management of construction and demolition debris should be crafted carefully. Recycling can provide environmental and economic benefits; by removing recycling barriers increased recycling can enhance these benefits. Recycling of C&D debris can potentially cause environmental harm if certain materials are not handled and used properly. Policies to prevent environmental and human health harm caused by recycling can actually decrease the amount of current recycling activity. It is important that policy implemented to increase recycling does not promote environmental harm and that policy implemented to decrease environmental harm does not unnecessarily decrease recycling. Understanding of the markets and barriers in the recycling industry is equally important to understanding of the science of potential environmental and human health effects from recycling and reuse of C&D debris. Once there is a thorough and reasonable understanding of the tradeoffs a balance needs to be found that will promote environmentally conscious recycling of C&D debris.

Consumer Demand

Trends in societal attitudes have shaped the way C&D debris is managed in the free market. For instance, recycling facilities are recognizing the change in societal attitudes towards sustainable development and a trend toward more “green” or high performance buildings. Many facilities recognized that the demand for their services is in part due to the demand for LEED certified buildings and the need for tracking
recycling rates for LEED certification. So, although the disposal economics may not be working in favor of recycling facilities in some regions of the US, societal tastes and preferences for more sustainable disposal options are valued higher than non-sustainable disposal options; thereby creating demand for recycling in regions where landfill tipping fees may be lower than recycling fees.

It is expected that 25% of all new construction will be LEED registered in the United States (Frost & Sullivan, 2008). Not only are consumer tastes and preferences driving the increased demand for high performance, LEED certified buildings, but increasing energy prices and energy supply concerns are also driving demand for the lower energy consuming buildings. The more awareness builders and industry obtain through their involvement in LEED projects awareness will infiltrate to the consumer and increase the demand for such buildings, which require recycling of the construction and demolition debris for certification.

**C&D Debris Definitions**

Lack of consistency in state definitions of C&D debris waste streams has caused difficulty in estimation and consistent management of C&D debris wastes nationally (US EPA 1998; US EPA 2008a; Clark et al. 2006). Establishment of a federal definition for the building-related C&D debris waste stream could have positive benefits. A federal definition would have to explore current state C&D debris waste definitions, especially of those states that have created significant management standards and regulations regarding C&D debris waste and take those into consideration when defining the waste stream.

A definition of C&D debris excluding bridges and roads could be useful since the types and composition of those wastes generated from roads and bridges are different.
than those generated from buildings (US EPA, 1998; US EPA 2008a). This could help quantify the amount of waste generated from building related activities and would be useful because management and issues of building related wastes are different than road and bridge wastes.

Establishing a federal definition could cause some problems for states with conflicting definitions; however, states with no definition may find this to be very beneficial for establishing management guidelines. Most existing state definitions are quite similar to one another. Prior research has also suggested that the federal government establish a C&D debris definition for more efficient research and the ability to more uniformly deal with problems in the waste stream (Clark et al. 2006).

**Recycling Barriers**

Some of the recycling barriers that were introduced in the literature review will be discussed and analyzed, and recommendations will be made based on the findings of the survey and available science. The barriers that will be discussed are: [1] Low value of recycled material; [2] low cost of landfill construction due to lack of requirements for liners, leachate collection systems, and groundwater monitoring; [3] low landfill tipping fees due to lack of technical requirements in C&D debris landfills for liners and groundwater monitoring; [4] lack of markets for certain materials.

**Low Value of Recycled Materials**

Recycled content materials have a relatively low value compared to the value of virgin resources. For instance an incineration plant that uses wood chips as biofuel will pay approximately 30% more for virgin wood chips as opposed to C&D debris wood chips (Daigle, Personal Communication 2008; Hixon, Personal Communication 2008).
Simple microeconomic theory says a shift in the demand curve due to changes in consumer tastes and preferences demand for more recycled content materials, will increase the price. Therefore, if there were a higher demand for recycled content materials there would be less opportunity cost for more C&D debris recycling firms to begin operation and less risk to those facilities making large investments.

**Landfill Costs**

There are two recognized recycling barriers linked to landfills. One is that the cost of constructing a C&D debris landfill is relatively low due many state’s lack of requirements for liners, leachate collection systems, and groundwater monitoring. The second is that with low construction costs of C&D debris landfills, the landfill is then able to charge low tipping fees.

Disposal consumers will naturally choose the least cost method of disposal (including transportation costs) unless they have some incentive to choose a higher cost method (e.g. LEED certification). Landfill tipping fees are also a function of landfill space availability in a region, permitting costs, and structural requirements for landfills. Landfill space availability is determined by two main factors which positively correlate with each other and with the price of these factors. The cost of purchasing open space is determined by the scarcity of open space in any specified area. Densely populated areas, such as the Northeast where land availability is scarce will have higher land prices and therefore, higher costs to purchasing land for a landfill. The other factor, reluctance of a community to accept a landfill can indirectly increase the cost of siting a landfill due to regulatory processes and pressure from communities to prohibit a landfill which will cost the landfill company money. Densely populated areas are more likely to object to landfill
siting because more residents will be affected (Jenkins, 1993). Communities object to living near a landfill due to the fear of environmental degradation, undesirable odors, an unattractive landscape, and heavy truck traffic.

Regulation has been set in place that requires MSW landfills to have liners, leachate collection systems, and groundwater monitoring requirements (Jenkins, 1993). There are also a multitude of hydrologic tests and research conducted when siting a MSW landfill. These regulations have in turn increased operating costs for MSW landfills and passed the increased costs to consumers in the form of higher landfill tipping fees.

On the other hand C&D debris landfills do not have the same federal structural and monitoring requirements that MSW landfills have. C&D debris is generally defined by states as being inert and therefore not readily reactive with other elements and not exhibiting the same environmental risks that the MSW waste stream has. However, research has shown that there are enough materials present in the C&D debris waste stream to cause environmental and human health problems (Weber et al. 2002; Townsend et al. 2004b; Jacobi et al. 2007b). Some states have decided that more stringent landfill requirements are necessary to protect environmental and public health. Not all states have enacted regulations that may be necessary to ensure environmental and human health integrity by imposing requirements for C&D debris landfills to have liners, groundwater monitoring, and leachate collection systems.

Construction costs for C&D debris landfills are relatively low when compared to the very high investment required for construction and operation of a mixed material C&D debris recycling facility, especially one with a high recycling rate. In 1998 it was estimated that a facility accepting 400-500 tons/day requires $300,000 to $750,000
investment in equipment (Peng et al. 1998). C&D debris recyclers handle low valued material; therefore, a facility needs to process a substantial volume and have access to stable markets to return the necessary revenues for operation.

C&D debris recyclers also have to compete with low landfill tipping fees. Therefore, the recycler must keep their tipping fee as low or lower than a landfill that will accept C&D debris in the area. In the Northeast tipping fee prices are not as problematic as other regions of the US, especially the Midwest where tipping fees are as low as $4.00 to $5.00 per ton in C&D debris landfills. Areas where the cost of landfill disposal is higher the recycling facilities have more ability to be competitive with the landfill tipping fees.

Twenty seven states allow C&D debris to be disposed in unlined landfills (excluding hazardous wastes that are regulated by the federal government) and some states may restrict other materials (Clark et al. 2006). Unlined landfills have relatively low construction costs and therefore can pass on lower landfill tipping fees to the disposal consumer. As an example, the cost to a landfill operator to install a composite liner for a one acre cell in a landfill is estimated to cost $500,000 per acre. If that acre were able to hold 900,000 cubic yards of waste it would translate into approximately 550,000 tons. The cost of this composite liner would add approximately $0.90 per ton in tipping fees. If requirements were added that C&D debris landfills needed a leachate collection system, the added cost to the landfill operator would be approximately $150,000 per year. If the landfill accepted 100,000 tons per year, it would add $1.50 per ton, more or less according to the expected tons anticipated annually at the landfill. Finally, requirements for groundwater monitoring would cost a landfill approximately $100,000 per year, again if the landfill accepted 100,000 tons per year it would an additional $1.00 per ton
in tipping fees. If landfill regulation required all three systems in C&D debris landfills, the approximate added cost in tipping fees per acre of landfill space in a landfill accepting 100,000 tons per year would be approximately $3.40. This cost would vary depending on the footprint size of the landfill, the tons accepting annually, and the airspace available. Also, geographic and hydrologic characteristics may also affect these prices (Schilling, Personal Communication, 2008). While an added cost of $3.40 per ton may seem relatively small, in Ohio, the current C&D debris landfill tipping fees are around $4.00 per ton. This would be an 85% increase in tipping fee price, which could be significant.

There are eighteen states that do not require liners, groundwater monitoring or leachate collection systems (Clark et al. 2006). These states could increase recycling opportunity by requiring C&D debris landfills to take steps which could increase recycling of C&D debris.

Waste Exportation

Some Northeastern states with high tipping fees and a high volume of C&D debris generated are exporting waste to lower cost states to reduce the cost of disposal. For instance, in 2002, the Northeast generated roughly 860,058 tons of C&D debris that was then disposed in states outside of the Northeast. It has been suggested that much of this waste is shipped by rail to Ohio for cheap disposal (Ohio Environmental Protection Agency, 2003; Cochran, 2006).

Not only is this problematic for states receiving the waste because of the landfill space and the transportation required to transport the waste from the Northeast to the Midwest may not be the most efficient use of energy. The energy would be more beneficially allocated if it were used on processing and production of recycled content
materials that may be used in a productive manner. Perhaps with rising energy and transportation costs the feasibility of exporting waste will diminish. Also, as suggested previously, increasing landfill tipping fees by requiring liners, groundwater monitoring, and leachate collection systems may also deter this waste exportation practice.

Lack of Markets

Some C&D debris materials have extensive and stable recycling markets and other materials have virtually no markets and the material is landfilled. C&D debris recyclers depend on revenues from tipping fees and the ability to sell the end products to new users and producers of the recovered material. When materials are not able to be sold the recycler must pay to dispose of the left-over materials in a landfill. If the material landfilled is one that does not have a reuse option due to environmental and human health risks then landfiling is probably the best use of such material; however, if environmental and human health risk is not the cause then expansion and development of markets would likely be beneficial.

Demolition Wood

Demolition wood is any wood that was once present in a building. Wood recovered from buildings may be treated with some other material. The wood may have been painted with oil based, water based, or lead-based paint or wood may have been stained or glued and drywall compounds may be present, and some wood is treated with CCA. These existing materials make recycling of demolition wood much more difficult than clean construction wood. Facility respondents reported that demolition wood represents, on average, approximately 14% of the incoming waste stream.
Recycling facilities are held to quality control standards required by the industry buying the products or by regulations at the state and federal level. The presence of potentially harmful materials on demolition wood makes recycling near impossible. It is difficult to determine what types of paints and other compounds are present on wood in the chaotic, fast-paced environment in C&D debris recycling facilities and the quantity of C&D debris present at a recycling facility makes finding a few pieces of wood tainted with hazardous materials even more difficult to identify.

Currently, demolition wood has very minimal recycling opportunity. Respondents of the survey said that 38% of recycling facilities that accepted demolition wood ended up using it as biofuel, 31% of facilities said that they landfilled it. A few facilities indicated that they were worried about changes in state regulations that would prohibit the use of CCA-treated wood as biofuel and therefore would eliminate the facility's ability to sell the biofuel to energy producers.

New Hampshire's legislature has recently decided that the environmental risk associated with burning demolition wood and toxic air pollution linked to lead based paint is not worth the risk. New Hampshire has decided to uphold their decision not to allow incineration of demolition wood as a source for energy (C&D debris task force, 2008). New Hampshire's decision to prohibit incineration of demolition wood has shown that environmental and human health concerns outweigh any potential benefits that may come from biofuel for that state.

States that do allow incineration of demolition wood have very strict specifications to minimize potential air pollution from materials present in the waste stream. C&D debris recyclers have to be cautious about the incoming feedstock of...
materials to help ensure that their biofuel materials meet state specifications. Some incinerators will have stockpiles of wood chips tested by an independent third party prior to the wood chip delivery to the incinerator. If the wood chips fail the specification test the recycling facility will not be able to sell the wood chips to the incinerator (Daigle, Personal Communication, 2008) and may be disposed in a landfill, which in some states may be unlined (Hamlin, Personal Communication, 2008).

Incinerators of the C&D wood have double accountability for the quality specifications of the incoming wood. The specifications are based on the pre-burn mix to determine the metals content of the ash and the air emissions resulting from the incineration, Table 8 is an example of Maine's fuel quality standards for incineration of C&D debris wood chips. The incinerator must pass air quality specifications and they must be able to dispose of the ash (MDEP, 2006). In Maine, the ash from incinerators has to be disposed in a special waste landfill due to the potentially high concentration of heavy metals in the ash (Hamlin, Personal Communication, 2008).

<table>
<thead>
<tr>
<th>Component</th>
<th>Allowable Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non Combustible</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Plastics</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>CCA-treated wood</td>
<td>&lt;1.5%</td>
</tr>
<tr>
<td>Asbestos</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>

Table 9: Maine Fuel Quality Standards for C&D Debris (MDEP, 2006)

Although there are a few different kinds of treated wood in the C&D debris waste stream, CCA-treated wood has hazardous waste characteristics that may pose environmental problems if mismanaged. CCA-treated wood is no longer produced; therefore, CCA-treated wood will be present through demolition and renovation activities.
CCA-treated wood should be carefully managed. Disposal of CCA-treated wood in unlined C&D debris landfills is not encouraged. The CCA-treated wood can leach arsenic into groundwater supplies and cause arsenic levels to exceed primary water quality standards (Weber et al. 2002). Therefore, CCA-treated wood should either be recycled or disposed in lined landfills.

CCA-treated wood also can cause environmental and human health harm when recycled and reused. As discussed in the literature review CCA-treated wood causes environmental and human health problems when reused where clean construction wood can be used safely. If CCA-treated wood is present in mulch (where much of the clean wood is used) it can leach arsenic into groundwater that may be used for drinking. Therefore, it is important that C&D debris recycling facilities accurately separate all CCA-treated wood from non-CCA treated wood prior to resale and reuse.

The use of the XRF hand scanners previously mentioned in the literature review may be very useful to aid a recycling facility in accurately separating CCA-treated wood from non-CCA-treated wood. If the XRF hand scanners prove to be reliable, affordable, and workable in the recycling facility environment their use should be encouraged. Accurate separation of the CCA-treated wood would decrease risk for the reuse of C&D debris wood as mulch and biofuel. Accurate separation may also expand market potential for recycled products made with C&D debris wood due to less risk of environmental and human health damage (Jacobi et al. 2007a).

Scientific research has potentially found some ways to minimize or eliminate toxins present in CCA-treated wood. It has been suggested that given a significant stock of CCA-treated wood it could be possible to remove the metals from the wood and allow
recycling of the wood and the metals extracted. However, this technique would require stockpiling a significant amount of CCA-treated wood which has the potential to leach significant amounts of heavy metals into water supplies if stockpiles are not properly covered, lined, and monitored (Jambeck et al. 2006a).

Demolition wood has a few barriers to increase its recycle-ability. However, with creative market expansion and research these barriers can be diminished and decrease the amount of demolition wood that is currently landfilled.

**Carpet**

Carpet is another material that doesn’t have many recycling opportunities. Only 68% of the facilities responding to the survey accept carpet at their facility and of those facilities accepting carpet 57% reported that they end up landfilling the carpet. The remaining 43% of facilities said the carpet was recycled into new carpet, poly fibers, ADC, and other uses.

In the US approximately 3 million tons of carpet are produced each year and 2 million tons are discarded annually only 1% of the discarded carpet is actually recycled (Fishbein, 2000). Carpet represents approximately 1% of the MSW stream. However, carpet often is a component of the C&D debris waste stream. Accurate estimations of the amount of carpet disposed are difficult due to potentially double counting.

Carpet has limited recycling opportunity due to the compositional characteristics of the product. Most carpet is not produced to be recycled. However, carpet can be sheared and chemically treated to be used as recycled nylon. The collection costs can cause recycling of carpet to be infeasible. Most US manufacturers are finding that by producing carpet to be recyclable the company will potentially see greater profits in the
future. However, the changes in the production processes of manufacturers will not be seen by the waste managers for another decade or more. Manufacturers are also implementing take-back programs and will recycle not only their own products but other manufacturers as well (Lave et al. 1998; Fishbein, 2000).

Carpet needs further research to establish safe and stable reuse opportunities for post consumer carpet products. But also encouraging stabilization of some of the existing markets for products produced from recycled carpet needs to be done. The Carpet America Recovery Effort (CARE) is a joint industry and government organization trying to promote and increase markets to increase the volume of recycled carpet. Support for such initiatives should be encouraged.

**Hazardous Materials**

Although federal law requires the proper removal and management of hazardous materials that are present in a building; this often does not happen (Townsend et al. 2004). The survey showed that some C&D debris facilities mentioned hazardous materials as one of the biggest problems their facility faces, suggesting that these materials are not properly removed and managed prior to building demolition or renovation.

Enforcing and or creating incentives for proper removal of hazardous materials prior to demolition or renovation will minimize the risk and occurrence of these substances in the recycling waste stream and increase the quality of the products recyclers supply. C&D debris recycling facilities have to spend a lot of money on quality control of their outgoing products. If a load is contaminated it may be that the C&D
debris recycler is not able to sell the material and may lose the potential revenue from the material.

Not only does contamination hurt the bottom line for a C&D debris recycler it can be problematic for consumers and the environment. If a contaminated load is unnoticed and the material is sold for reuse it could cause environmental and human health problems.

**C&D Debris Fines**

C&D debris fines management is a major component of this thesis. C&D debris fines are inevitably going to be created through the sorting process and need to be managed and disposed properly. The survey of C&D debris recycling facilities shed some light on national management of C&D debris fines. Current C&D debris facility practices and experiences are important for policy and management recommendations.

**Management**

C&D debris fines used as ADC have caused some odor nuisance problems and a few human health issues. For example, a landfill in Southeastern Maine stopped accepting C&D debris fines from a recycling facility due to the odor complaints from H₂S formation from local residents. The recycling facility had to find a different landfill to accept the C&D debris fines. Other landfills have installed H₂S gas collection systems to alleviate the problem (Hamlin, Personal Communication, 2008). H₂S collection systems for a one-acre cell and one flare can cost approximately $800,000 for closure and post-closure care of a landfill (Jambeck, Personal Communication, 2008).

Management requirements for C&D debris fines need to take into consideration regional environmental factors that can affect the consequences of certain management
practices. Rainfall and temperature are environmental factors that may be distinguishable by regional characteristics and contribute to the generation of H$_2$S. Other landfill environment factors which are not distinguishable by regional characteristics include the amount of organic matter, the amount of dissolved oxygen in the leachate, and the pH (Jambeck et al. 2006). Policy and management decisions for C&D debris fines used as ADC and/or shaping and grading at landfills undergoing closure, should consider the environmental factors of the region.

The survey of mixed C&D debris recycling facilities found the only serious issues with hydrogen sulfide formation and the most common use as ADC in landfills was in the Northeast. Therefore, policy makers in the Northeast should know that there are environmental factors contributing to H$_2$S formation. The Northeast also has high landfill tipping fees; therefore, recycling of C&D debris is in higher demand.

Policy makers in the Northeast need to be aware of the tradeoffs when implementing policy and management requirements. Prohibiting the use of C&D debris fines as ADC would negatively impact C&D debris recyclers and could possibly result in their closure, but policy needs to ensure that hydrogen sulfide formation does not exceed levels which cause negative health effects.

Rainfall and the quantity of recycling in the Northeast may be two contributing factors to the serious issues of hydrogen sulfide formation experienced in the Northeast. Figure 30 was obtained from the National Oceanic and Atmospheric Administration (NOAA), this illustration shows average annual precipitation levels throughout the US. The Northeast as a region experiences the most annual precipitation. The available science does conclude that rainfall and H$_2$S generation are positively correlated. The
survey findings showed that only the Northeast respondents had serious issues with hydrogen sulfide formation, and the Northeast also experiences the highest precipitation levels.

The West, which is the driest region; excluding Washington and Oregon states, may not need to worry about \( \text{H}_2\text{S} \) formation when C&D debris fines are used as ADC. Therefore, it may not be necessary to introduce policy to prevent \( \text{H}_2\text{S} \) formation. Nonetheless, policy makers and C&D debris recycling facilities should be aware of what causes \( \text{H}_2\text{S} \) so they may possibly take steps to prevent it from occurring in the future.

The Western C&D debris recyclers reported the most "I do not know" responses about whether or not they had experienced \( \text{H}_2\text{S} \) formation from their C&D debris fines. This could mean one of two possibilities: There is not hydrogen sulfide formation and therefore it has not been brought to their attention; or, landfill operators and recyclers do not want to look for a problem which will make their business operations more difficult.

The Midwest facilities did not report any instances of hydrogen sulfide formation from their C&D debris fines. There are different factors which could contribute to this: relatively less rainfall; less recycling in the region therefore, less C&D debris fines to dispose; and the use of C&D debris fines in non-landfill environments.
Typically the southeast region where rainfall is more prevalent would have more susceptibility to H$_2$S generation. Although facilities did not report any instances of H$_2$S generation being serious enough to prompt mitigation the region does have some climate characteristics that may result in H$_2$S generation. Perhaps the south does not need policy that will be as stringent and preventative as that of the Northeast, but to err on the side of caution some policy could be made to prevent serious problems in the future.

Currently gypsum concentration measurement methods are being created (Musson et al. In Press). If these methods are cost effective and simple to conduct this could help more accurately predict the threshold concentration levels of gypsum in C&D debris fines for different regions for H$_2$S formation in landfill environments. The level of H$_2$S production in landfills can be directly correlated with the gypsum concentration in the C&D debris fines (Jambeck et al. 2006). Facilities could then measure the gypsum
content in their C&D debris fines to determine if dilution is necessary to prevent H₂S formation that could potentially be problematic considering the characteristics of the region.

Most facilities did seem aware of the potential for H₂S formation; however, 22% of the facilities which handle C&D debris fines did not know whether or not H₂S formation was occurring. It is not known whether or not the facilities understand causes of H₂S formation because they were not asked. However, it is possible that simply educating facilities about the potential for H₂S formation due to the presence of gypsum drywall in C&D debris fines when used as ADC at landfills could prevent future problems.

Participants in the survey also reported steps that they had taken to help reduce the potential for H₂S formation. Some examples of the action facilities reported included: no longer accepting full truckloads of gypsum drywall, composting the construction drywall, and implementing a gypsum removal program where the whole sheets of drywall are removed while the debris is on the tipping floor.

Some facilities reported that they had taken steps to prevent H₂S formation even though they had not yet experienced any H₂S formation problems from their C&D debris fines. This possibly suggests that facilities are willing and able to take the necessary steps to prevent H₂S generation and may find it in their benefit to prevent H₂S generation to preserve their ability to dispose of the C&D debris fines in landfills. The mitigation steps do cost the recycling facilities money. The labor associated with removal of gypsum from the incoming loads requires extra time and labor. Also, the demolition drywall that is removed from the waste stream needs to be disposed in a landfill and the
recycler must pay for that disposal (Hixon, Personal Communication, 2008). Therefore, requirements for gypsum removal programs can be costly and therefore should be cautiously mandated. Areas with lower risk for potential H$_2$S formation should not be stringently forced to take mitigation procedures (Hixon, Personal Communication, 2008).

Scientific research to identify a means to attenuate H$_2$S formation in the landfill environment is currently being conducted by environmental engineers. Attempts have been made to mix C&D debris fines with other materials in hopes that the dilution of the C&D debris fines and the composition of the other materials will help dilute and attenuate the H$_2$S formation.

A research group at the University of New Hampshire is currently investigating H$_2$S attenuation with materials (ex-situ) and mixing materials with C&D debris fines simulated landfill environments (in-situ) to determine whether using an amendment will help attenuate and decrease the formation of H$_2$S. The research group has found some materials including: wood ash, cement kiln dust, waste-to-energy ash, have potential to attenuate hydrogen sulfide generation in a landfill (Loazia et al. 2008).

**Testing**

Testing is required at the state level for the use of C&D debris fines as ADC at landfills. Some states have much more stringent laws than others. For instance, New Hampshire requires that recycling facilities frequently test the C&D debris fines for heavy metals and other potentially harmful materials as a part of the beneficial use determination (BUD) permit (Hamlin, Personal Communication, 2008). Other states, like Maine, only require a recycling facility to show that the C&D debris fines are consistently characterized by providing samples of the C&D debris fines and that they do
not have the presence of heavy metals, arsenic, and other harmful materials prior to the issue of a BUD permit. Once the BUD permit is issued the recycling facility no longer has to test or provide samples to the state. (Hamlin, Personal Communication). Landfills accepting C&D debris fines for ADC also may have criteria that the C&D debris fines must meet, this is not a state regulation, but can affect whether or not recycling facility will test the C&D debris fines and how frequently (Hamlin, Personal Communication, 2008; Hixon, Personal Communication, 2008).

The survey found that most facilities did not test their C&D debris fines. Recycling facilities which are using C&D debris fines for non-landfill uses should especially actively test their C&D debris fines. When C&D debris fines are used for purposes where leaching can occur into public water supplies and public lands testing for heavy metals should be mandatory to protect public health and the environment.

Studies have found that some heavy metals have been found to be present in C&D debris fines. It was found in Florida that arsenic levels in C&D debris fines were high enough to cause environmental and potentially human health impacts. Also, sulfur levels have been found to exceed secondary pollutant levels in leachate from C&D debris fines (Townsend et al. 2004; Jang and Townsend, 2001). When C&D debris fines are disposed in a landfill where liners, leachate collection, and groundwater monitoring are present, testing for these heavy metals may not be as critical. However, as a precautionary procedure, facilities intending to have C&D debris fines used outside of landfill environments should test C&D debris fines on a regular basis to ensure environmental and human health risks are minimized.
Requirements for testing need to be cautious and aware of the costs to conduct these tests. Table 10 gives the prices for common tests conducted on C&D debris fines used as ADC. The costs of the tests need to be considered prior to regulatory requirement for these tests and their frequency. Finding a balance that limits frequency yet provides environmental and groundwater protection is necessary.

<table>
<thead>
<tr>
<th>Test</th>
<th>Price*</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAH (Includes Semi-Volatile Organics)</td>
<td>$156.00</td>
</tr>
<tr>
<td>TCLP for Metals</td>
<td>$219.00</td>
</tr>
<tr>
<td>Total Metals</td>
<td>$139.00</td>
</tr>
<tr>
<td>Volatile Organics</td>
<td>$187.20</td>
</tr>
<tr>
<td>Sulfate</td>
<td>$40.00</td>
</tr>
<tr>
<td>pH</td>
<td>$13.00</td>
</tr>
</tbody>
</table>

Table 10: C&D Debris Fines Testing Prices (Groundwater Analytical, 2008)

**Landfill Collaboration**

Landfill and mixed C&D debris recycling facility collaboration can be beneficial for landfill operators, recycling facilities and society. Landfills benefit because a ton of C&D debris takes up more air space than a ton of MSW. On average, mixed C&D debris is 484 pounds per cubic yard and does not compact in a landfill environment like typical MSW waste does. The average normally compacted MSW in a landfill is 760 pounds per cubic yard (Tchobanoglous et al. 1993). Therefore, airspace is saved by diverting C&D debris, since most landfills charge by the ton rather than by the cubic yard, the landfill will be conserving airspace and increasing revenues by accepting materials that minimize airspace. Recyclers benefit because they have more feedstock which they can in turn, sell as processed output (Hixon, Personal Communication, 2008). Society benefits because

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* Prices may vary by company, contract, days for turn around, and state requirements.
landfill space is saved, there is less demand for virgin materials, and ultimately less environmental harm.

The mixed C&D debris recycler survey found that 14% of recycling facilities do collaborate with landfills to divert C&D debris materials to recycling. The collaborating facilities reported how many tons were annually diverted from landfills; the percentage of their total annual feedstock ranged from 9% to 67% with an average of 24%.

The amount of C&D debris that is diverted from landfills through collaboration is quite significant. Promotion of collaboration could help increase C&D debris recycling rates. Possibly, simply introducing landfill and recycling facility operators to the idea and educating both parties about the potential benefits to their own facilities could increase those facilities and landfills that are collaborating.

**Fostering & Attracting Recycling Facilities**

The survey gave some insight into some community and governmental characteristics that C&D debris recycling facilities found to be appealing for facility siting. As stated in the summary of survey findings interstate access, state tax structure, local acceptance, and demand for recycling services are very important considerations for C&D debris recyclers when choosing a location to site a facility.

Regions with high demand for C&D debris recycling services can look to the communities within the region to determine if they can invite a C&D debris recycler to operate. Communities without high demand for C&D debris recycling may increase the demand for C&D debris recycling services by mandating and/or encouraging the
recycling of C&D debris. The establishment of demand is critical to any successful recycling operation.

The other characteristics that C&D debris recyclers look for in the communities that site operations may not be easily changed. Interstate access, local acceptance, and state structure are hard to change. However, communities that have these characteristics may be able to sell themselves to the C&D debris recycler.

**Conclusions**

Construction and demolition debris is a significant waste stream that faces management issues and is currently being targeted by all levels of government for reduction, reuse, and recycling. Policy makers need to understand and take into consideration current industry practices, economics, and environmental implications of different management options. By understanding these different aspects prior to the decision making process policy makers will be able to make the most educated management requirements and minimize potential negative side effects of such policy.

Different regions and states of the US are facing different C&D debris management issues and current trends. Local policy makers should look at their own region’s characteristics. For instance, management recommendations for C&D debris fines needs to look at the potential environmental impacts of landfilling C&D debris fines. In the Northeast where the climate is more wet there is more potential for H$_2$S formation when used as an alternative daily cover in landfills. Therefore, mitigation steps should be taken to reduce the potential for H$_2$S formation in the Northeast.

Current consumer tastes and preferences for more sustainable and “green” building practices are contributing to increased demand for C&D debris recycling. If the
demand for green buildings including LEED certified buildings continues to grow then
there will be an increase in demand for C&D debris recycling services. The C&D debris
recycling industry is recognizing this as a contributing factor of increased demand and is
implementing services at their facilities for those interested in obtaining LEED building
certification. If sound policy can be made to increase recycling and minimize negative
environmental impacts from, land disposal, incineration, and recycling management
techniques, our society, environment and natural resource stocks will benefit.

The recommendations made in this thesis are made using the available
science, current regulations, and industry practices. Caution and consideration should be
given to all variables, geographic, and demographic characteristics for any given
geographic or market area, prior to any policy or management requirement changes.
Tradeoffs may need to be made between economic efficiency and environmental and
public health; such tradeoffs need to be examined thoroughly and use of all available
science is critical. Other benefits would be increased employment opportunities with
higher pay, less demand for virgin materials, decreased pressure on landfill space,
decreased emissions, and preservation of natural resources for future generations.
REFERENCES


Center for Disease Control and Prevention (CDC). “Preventing lead poisoning in young children.” Available online at: http://www.cdc.gov/nceh/lead/publications/books/plpyc/chapter8.htm#References


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APPENDICES
APPENDIX A

A National Survey of C&D Recycling Facility Practices

The University of New Hampshire

A collaborative effort between the Department of Resource Economics & Development and the Department of Civil & Environmental Engineering
All information provided will remain confidential. If however, there are any questions that you wish not to answer, please feel free to leave answers blank.

1. How many part and full time employees does this facility have?
   
   _______ Full-time _______ Part-time

2. How many acres are actively utilized by the facility for its recycling operation?
   
   ________ acres

3. Approximately, how many tons of mixed construction & demolition (C&D) debris does your facility accept per year?
   
   ________ tons per year

4. How many tons of C&D materials are *permitted* to be accepted per year at your facility?
   
   ________ tons per year

5. Does your facility have an on-site landfill? Check all that apply:

   □ Yes, we have an on-site C&D landfill
   □ Yes, we have an on-site municipal solid waste (MSW) landfill
   □ No, we do not have an on-site landfill
6. Please check all the materials which are accepted at your facility and the approximate percentage of each incoming material.

Accepted

- Demolition Drywall _______%
- Clean Drywall _______%
- Concrete _______%
- Brick _______%
- Asphalt _______%
- Shingles _______%
- Carpet _______%
- Clean Wood _______%
- Demolition Wood _______%
- Ferrous Metals _______%
- Non-Ferrous Metals _______%
- Cardboard _______%
- Wood Pallets _______%
- Yard Waste _______%
- Other, please specify ____________________________ _______%
- Other, please specify ____________________________ _______%
- Other, please specify ____________________________ _______%
7. What are the end products (uses, markets, purchasers) for materials processed at your facility?

- Demolition Drywall
- Clean Drywall
- Concrete
- Brick
- Asphalt
- Shingles
- Carpet
- Demolition Wood
- Clean Wood
- Ferrous Metals
- Non-ferrous Metals
- Cardboard
- Wood Pallets
- Yard Waste
- C&D Fines
- Other, please specify
- Other, please specify
- Other, please specify
8. What is your facility's diversion/recycling rate (e.g., out of x tons what percentage is made into reusable product)?

_______%

9. Please check all separation mechanisms your facility uses when processing material:

☐ Magnets (Type/How many)

________________________/_______: ____________________/_____

☐ Eddy Current Separator

☐ Grinding

☐ Screening

☐ Float Tank

☐ Air Classifier

☐ Picking Line (Number of workers)___________

10. How are the C&D fines managed?

☐ Go to a landfill for daily cover

☐ Shaping & Grading

☐ Other, please specify ________________________________
11. Who pays for the management of the fines?

☐ The landfill accepting them for daily cover or shaping & grading pays us for the fines.

☐ We pay for the landfill to accept the fines daily cover or shaping & grading

☐ Other, please specify ________________________________

12. Which party is responsible for hauling the fines?

☐ Our facility

☐ The landfill

☐ Other, please specify ________________________________

13. Has this facility experienced any issues with hydrogen sulfide formation from your fines?

☐ I do not know if we have experienced issues with hydrogen sulfide formation

☐ No, we have not experienced issues with hydrogen sulfide formation

☐ Yes, we have experienced issues with hydrogen sulfide formation but it has not been serious enough to prompt mitigation.

☐ Yes, we have experienced issues with hydrogen sulfide formation and have taken action to mitigate the formation.
14. If your facility has experienced issues with hydrogen sulfide formation, what has this facility done to mitigate the formation of hydrogen sulfide in the fines? If you are still exploring options for mitigation please state so.

________________________________________________________________________

________________________________________________________________________

15. What is the final screen size used when processing fines

☐ 3/8 inch
☐ ½ inch
☐ ¾ inch
☐ 1 inch
☐ 2 inch

☐ 3 inch
☐ 4 inch
☐ 5 inch
☐ 6 inch
☐ Other, please specify _________

16. How often are fines tested?

☐ Daily
☐ Weekly
☐ Monthly

☐ Other, please specify below: _____________________________________________

☐ Every 1,000 tons
☐ Every 5,000 tons
☐ Every 10,000 tons

☐ Other, please specify below: _____________________________________________

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17. Are any of the following tests conducted the fines? Check all that apply:

☐ PAHs
☐ Total Metals
☐ Semi-Volatile Organics
☐ Other, please specify below:

☐ Volatile Organics
☐ Sulfate
☐ TCLP for metals
☐ pH

18. Does the community where this facility is located have any ordinances requiring recycling for construction & demolition debris?

☐ No, this community does not have an ordinance requiring C&D recycling

☐ Yes, this community has an ordinance requiring ______ % of materials to be recycled.

Which government is this required by? (Circle one)

Local    County    State

☐ I do not know
19. Did this facility experience any siting issues from any of the following? Check all that apply:

- [ ] Yes, the local community
- [ ] Yes, the county government
- [ ] Yes, the state government
- [ ] Yes, the Federal government
- [ ] No, this facility did not experience any siting issues from any of these governments.

20. What did these issues concern, and how long did these issues delay operation? Please briefly describe these issues:

Resulting in a delay in operation for ________ months

__________________________________________________________________________

__________________________________________________________________________

__________________________________________________________________________

21. Would it be possible for your facility to track a client’s recycling rate (% recovered from loads dropped off) for any given project?

- [ ] Yes, we track client’s recycling rates
- [ ] Yes, this would be possible, but we have not done this
- [ ] No, this would not be possible
- [ ] I do not know if this would be possible
22. Please rate the following characteristics and their importance when siting this facility. 1 being not important, 10 being very important.

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<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<th>10</th>
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<tbody>
<tr>
<td>Railway Access</td>
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<td>Interstate Access</td>
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<td>Local Tax Structure</td>
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<td>State Tax Structure</td>
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<td>Demand for Recycling Services</td>
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<td>Other, please rate &amp; specify below:</td>
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</tbody>
</table>

23. What do you believe are the main factors contributing to demand for your facility’s services?

- [ ] Ease of access (location)
- [ ] Other, please specify below:
  __________________________________________________________
- [ ] Population density
- [ ] Natural disasters
- [ ] Growth & development
- [ ] Policy
24. Is this facility considering physical expansion in the next year?

☐ Yes, this facility is planning to expand by _________ sq. feet

☐ No, this facility is not considering expansion

25. What policy recommendations would you make to any level of government (city, county, state, or federal) to increase diversion rates of C&D debris from landfills to your recycling facility?

_________________________________________________________________________

_________________________________________________________________________

_________________________________________________________________________

_________________________________________________________________________

26. Does this facility collaborate with local (MSW) landfill(s) to receive the C&D debris that is delivered to the landfill?

☐ No, we do not collaborate with a landfill, there is not one nearby

☐ No, we do not collaborate with a landfill, although there is one nearby

☐ No, we do not currently collaborate with a landfill, but we are trying to do so

☐ Yes, this facility also operates a landfill

☐ Yes, we collaborate with a local landfill
27. If this facility collaborates with a landfill to divert C&D materials, approximately how many tons are annually diverted from the landfill to your facility?

__________________ tons annually

28. What is the approximate mileage to the nearest MSW landfill?

__________________ miles

29. What is the approximate mileage to the nearest C&D landfill?

__________________ miles

30. What material do you currently feel is the most problematic for your facility to manage, and in the next five to ten years, what material do you believe will be the biggest concern this facility deals with (i.e., compact fluorescent light bulbs, treated-wood) and why?

____________________________________________________________________________________

____________________________________________________________________________________

____________________________________________________________________________________
31. What are this facility’s tipping fees for the following clients that you may accept waste from:

<table>
<thead>
<tr>
<th>Category</th>
<th>Fee ($/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-contracted individual household</td>
<td>$_________</td>
</tr>
<tr>
<td>Non-contracted haulers</td>
<td>$_________</td>
</tr>
<tr>
<td>Contracted haulers</td>
<td>$_________</td>
</tr>
<tr>
<td>Non-contracted entities (e.g., municipality)</td>
<td>$_________</td>
</tr>
<tr>
<td>Contracted entities (e.g., university)</td>
<td>$_________</td>
</tr>
<tr>
<td>Other, please specify</td>
<td>$_________</td>
</tr>
</tbody>
</table>
32. On the following space provided please draw the geographic market area where 75% of your inputs come from. The x is where your facility is located. Please enter the approximate mileage distance in each direction (North, South, East & West).
33. Please, give the town and state of this facility:

________________________________________

34. If you would like to receive a summary of our findings please check the box below, address of this facility’s location will be necessary to distribute the findings. No Individual responses will be connected to any individual facility.

☐ Yes, I would like to receive a summary of the findings of this survey

This facility’s address is:

________________________________________

We would like to sincerely thank you for your cooperation in our survey.

If you have any questions you may contact:

Professor John Halstead at (603) 862-3914 or ram.info@unh.edu

Professor Jenna Jambeck at (603) 862-4023 or jenna.jambeck@unh.edu

Andria Vachon at Andria.vachon@unh.edu
This facility is not a mixed C&D Recycling Facility

*All photos of the demolition of Demeritt Hall located on the University of New Hampshire campus are courtesy of Nancy Brown, Department of Natural Resources. The debris was brought to a processing facility for recycling.
APPENDIX B

University of New Hampshire
Research Conduct and Compliance Services, Office of Sponsored Research
Service Building, 51 College Road, Durham, NH 03824-3589
Fax: 603-862-3564

05-Sep-2007

Vachon, Andria
Resource Economics & Development
309 James Hall
Durham, NH 03824

IRB #: 4060
Study: Environmental and Economic Issues with Recycling Construction and Demolition Debris: A National Survey
Approval Date: 29-Aug-2007

The Institutional Review Board for the Protection of Human Subjects in Research (IRB) has reviewed and approved the protocol for your study as Exempt as described in Title 45, Code of Federal Regulations (CFR), Part 46, Subsection 101(b). Approval is granted to conduct your study as described in your protocol.

Researchers who conduct studies involving human subjects have responsibilities as outlined in the attached document, Responsibilities of Directors of Research Studies Involving Human Subjects. (This document is also available at http://www.unh.edu/osr/compliance/irb.html.) Please read this document carefully before commencing your work involving human subjects.

Upon completion of your study, please complete the enclosed pink Exempt Study Final Report form and return it to this office along with a report of your findings.

If you have questions or concerns about your study or this approval, please feel free to contact me at 603-862-2003 or julie.simpson@unh.edu. Please refer to the IRB # above in all correspondence related to this study. The IRB wishes you success with your research.

For the IRB,

[Signature]
Julie F. Simpson
Manager

cc: File
Halstead, John

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